DEEP-SEA RESEARCH

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Vol.
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58-59

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Volume 5
1958—59

PERGAMON PRESS
NEW YORK · LONDON · PARIS · LOS ANGELES

MAXWELL REPRINT COMPANY
Elmsford, New York

DEEP-SEA RESEARCH

Editors

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First reprinting 1970.

Printed in U.S.A.

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Deep-Sea Research, 1958 Vol. 5, pp. 1 to 6. Pergamon Press Ltd., London

Deep-sea bathymetry north of Point Barrow*

R. L. FISHER†, A. J. CARSOLA‡ and G. SHUMWAY‡

Abstract—Favorable ice conditions in 1951 and 1957 allowed echo-sounding across the continental slope and into the deep basin north of Pt. Barrow, where a relatively smooth sea-floor between 2000 and 2100 fm deep was found. North-northwest of Pt. Barrow lies a continental borderland area containing a detached ridge 100 miles long with a steep (23°) southeast flank.

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INTRODUCTION

CONTINUOUS echo–sounder lines from anywhere in the deep basins of the Arctic Ocean are rare due to the fact that pack ice covers most of the area the year round. During the brief Arctic summer the shallow edges of the polar sea, underlain by the continental shelf, may become ice-free; in exceptionally good years it is possible for icebreakers to penetrate a short distance into deep–water regions. Favorable ice conditions during the summers of 1951 and 1957 made it possible to obtain many continuouous echo-sounding lines running over the continental slope and well into the deep basin north of Pt. Barrow, Alsaka.

A reconnaissance cruise made in 1950 by the icebreaker *U.S.S. Burton Island* obtained sounding lines along the continental slope north of Alaska and Canada as far east as Banks Island. In 1951 the *Burton Island*, with geological observations under CARSOLA, carried out an extensive survey between Banks Island (125°W) and the 170° meridian. Some results of the 1951 cruise have been published (CARSOLA 1954, a, b, c, d, 1955). In 1954 *H.M.C.S. Labrador* carried out a survey west of 157°W between 73°N and 75°N. In 1957 two icebreakers were used for survey work: M. A. BEAL and J. H. SHERMAN III, working from *U.S.S. Staten Island*, obtained bathymetric records and bottom samples from the continental shelf and slope northeast of Barrow; two of us (R.L.F. and G.S.), working from *U.S.C.G.C. Northwind*, obtained bathymetric data on the continental slope and deep–sea floor north of Barrow.

Bathymetric data for the ocean north of Alaska have been published by CRARY, COTELL and OLIVER (1952), WORTHINGTON (1953)†, CRARY (1954) and CRARY and GOLDSTEIN (1957). A bathymetric chart of the Arctic Ocean is presented in a Soviet publication (ANONYMOUS, 1954). Earlier bathymetric studies are summarized by EMERY (1949). PANOV (1955) discussed neotectonic movements in the Arctic region.

Russian investigations, as summarized on a small-scale chart (ANONYMOUS, 1954), suggest that an extensive area shoaler than 1650 fm (3000 m) separates the deep–sea floor northeast of Barrow from the far northern basins adjacent to Lomonosov Ridge (and the Marvin Ridge of CRARY and GOLDSTEIN, 1957). The present writers propose the name Beaufort Basin to designate the region deeper than 1900 fm (or 3500 m) extending from about 140 — 160°W and northward an unspecified distance

*This work was supported in part by Scripps Institution of Oceanography contracts with the Arctic Institute of North America and the Office of Naval Research. Reproduction rights in whole or in part permitted for any purpose of the United States Government.

†Also reported as unpublished technical reports of the Woods Hole Oceanographic Institution: HOLMES J. F. (1951) Report 51-67; HOLMES J. F. and WORTHINGTON L. V. (1953) Report 53-23.

from the continental slope north of Alaska. This paper presents bathymetry of the western portion of the Beaufort Basin and its western and southwestern borders (Fig. 1).

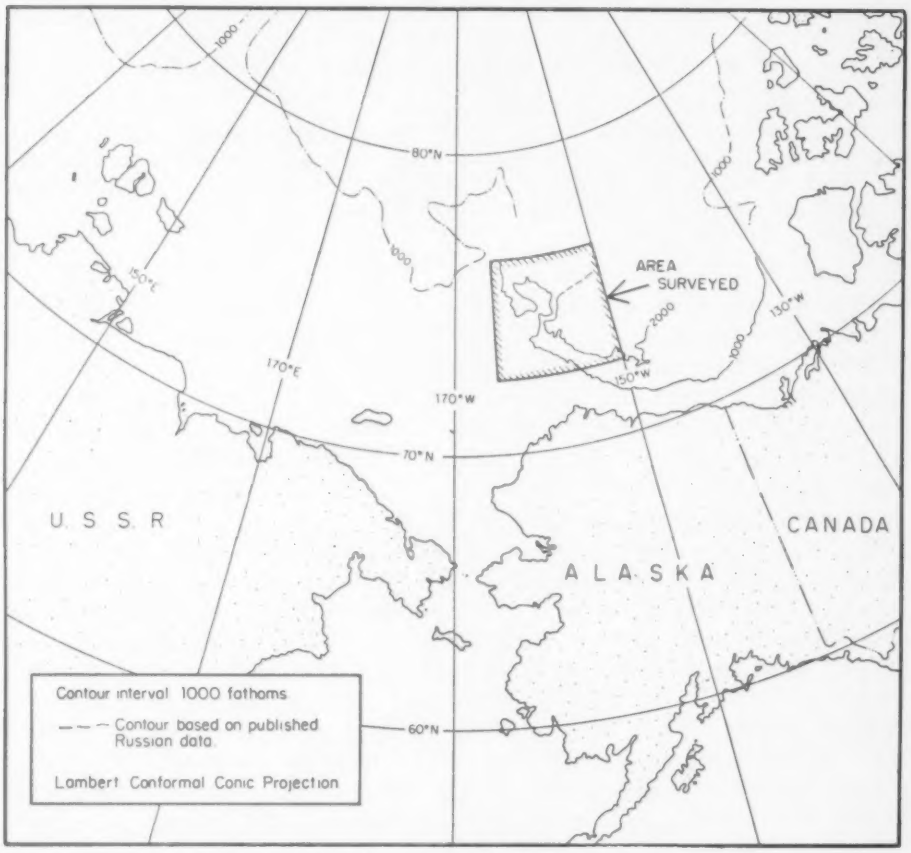

Fig. 1. Location of survey area in the Arctic Ocean.

DISCUSSION

The detailed bathymetric chart (Fig. 2) is a product of the 1950, 1951, 1954 and 1957 investigations only, except for the four spot soundings in the northeast sector of the chart. Only these four soundings have been corrected for the dependence of sound velocity on temperature and salinity of sea-water. The continuous lines were recorded with an assumed sounding velocity of 4800 ft (1463 m) per sec. This value is within 50 ft/sec, about 1 per cent, of the velocities for the Arctic Ocean employed by CRARY and GOLDSTEIN (1954, p. 187). It is greater than their shallow-water and less than their deep-water value. Slope corrections have not been applied. In traversing steep slopes, side echoes may arrive prior to returns from directly beneath the ship, resulting in an apparent sea-floor slope which is less than the true slope. This effect was noted along the N–S scarp north of 74°N, but the first recorded arrival was accepted as the depth.

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During the 1951 and 1954 investigations the survey ships obtained ship's position by Electronic Position Indicator (BURMISTER, 1951, p. 4). This method is particularly convenient when operating in ice areas where poor visibility, maneuvering and frequent speed changes make dead reckoning between celestial observations uncertain, at best. In the field, the 1957 survey positions were controlled by sun lines, and

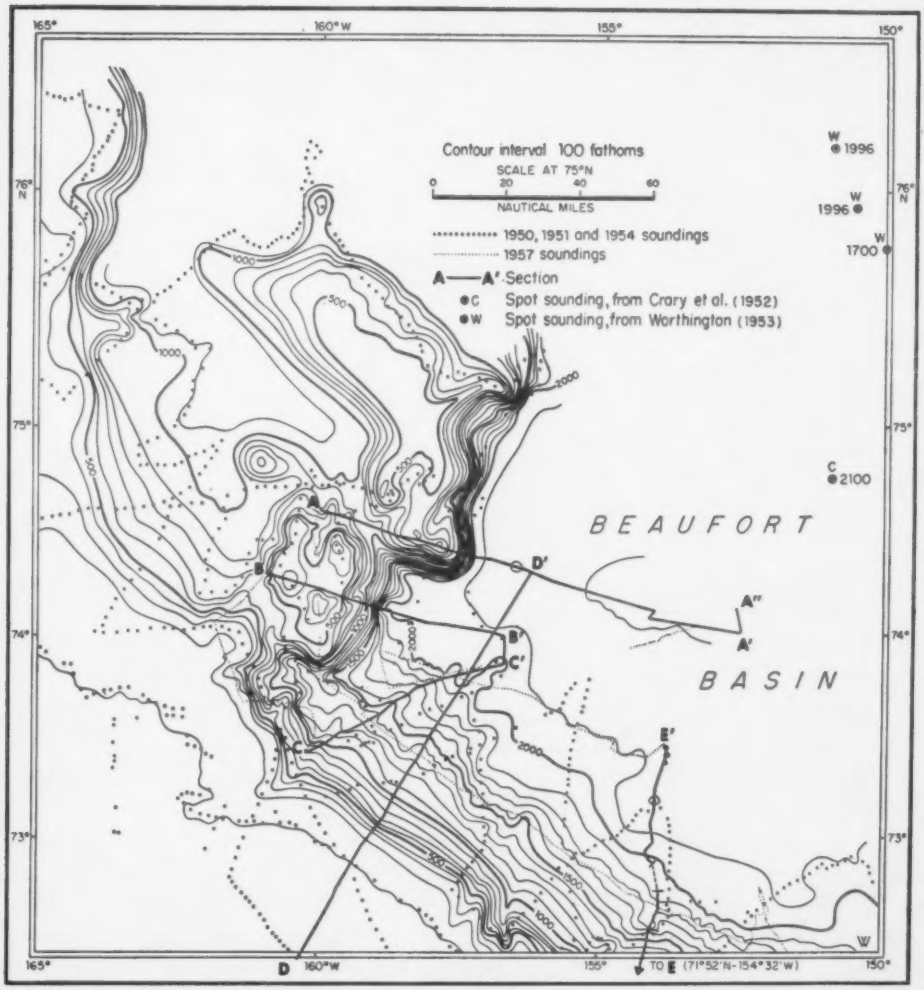

Fig. 2. Bathymetry for a portion of the Arctic Ocean north of Alaska, based on continuously-recorded echo-sounding lines. Sections A-A'', B-B', C-C'-B', and E-E' are along 1957 sounding lines. Section D-D' is along 1951 sounding line down to 1900 fm contour.

intermediate positions were determined by continuous radar tracking of large, distinctive ice floes to establish ship's speed and direction. The 1957 tracks have been transposed where depth crossings with the 1951 lines indicated adjustment was necessary. Where such crossings were unavailable, the 1957 lines have a probable error of $\pm$ 2 miles in position.

Four topographic characteristics of the area of sea–floor included in Fig. 2 should be noted; these characteristics appear clearly on the bathymetric cross-sections (Fig. 3).

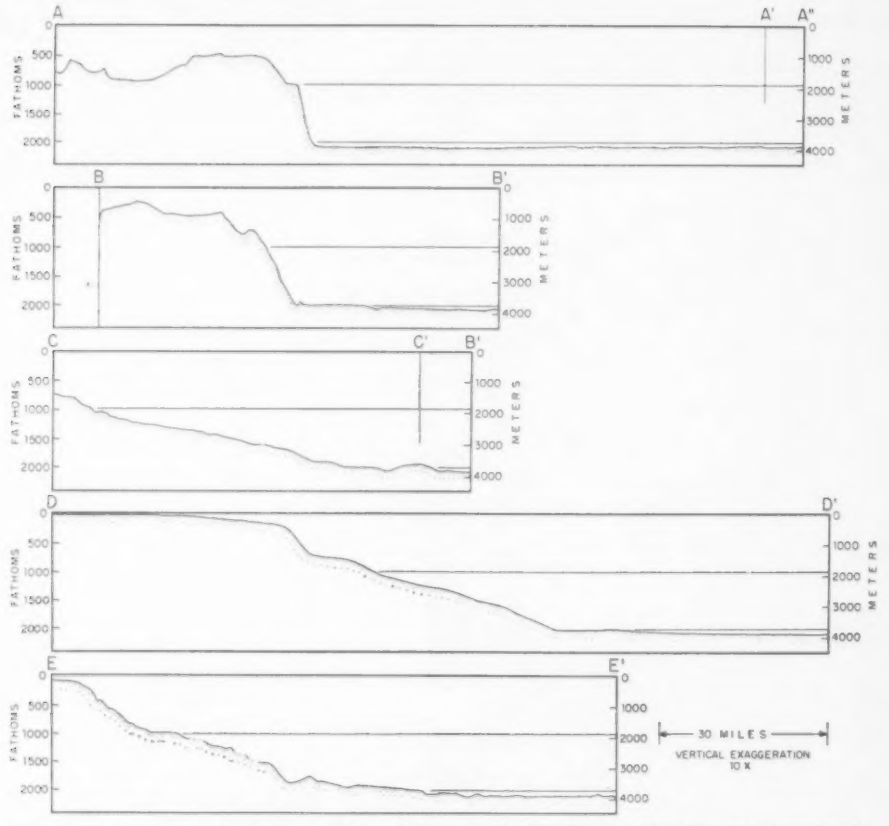

Fig. 3. Cross-sections down the continental slope north of Pt. Barrow (See Fig. 2 for locations).

First, the part of the Beaufort Basin now relatively well-explored, about 6000-8000 sq. miles in all, is nearly flat-bottomed at 2060 ± 60 fm (Fig. 3, sections A-A′, B-B′, D-D′). A slight rise lies northeast of 74°N, 155°W. The transition from continental slope to flat bottom is abrupt on the north-western sections. Apparently basement relief has been buried by a level-surfaced mass of sediment. Three of the four spot soundings (Fig. 2) suggest that this basin extends at least to 76°N, 151°W. The 1700 fm sounding may represent an isolated seamount or a ridge terminating the abyssal plain.

Second, from two normal and three oblique slope crossings in 1957 and well-controlled 1951 and 1954 soundings, the lower continental slope (below 1000 fm) is shown to be a steep scarp (23° on section A-A′) in the area west of the basin. This contrasts sharply with the lower slope to the southeast which ranges from 1°09′ to 1°56′ in three normal crossings between the vicinity of section C-C′ (Fig. 3) and the vicinity of the Mackenzie Delta. The lower slope becomes progressively gentler

proceeding southeast from the vicinity of the sharp bend between sections D-D′ and B-B′; the gradient north of the bend steepens abruptly.

Third, off the Alaskan coastal plain southeast of Fig. 2, the upper continental slope is steep, ranging from 4 to 10°. Off Pt. Barrow, where the shelf-break lies near 35 fm, a very gentle upper slope appears (CARSOLA, 1954a). This upper slope extends to greater depths and widens toward the north-northwest until in the region shown in the extreme northwest portion of Fig. 2 it extends to a depth of almost 500 fm. It is possible that this feature continues to widen and deepen toward the north-west, where it may ultimately join the broad area shoaler than 1650 fm described recently by the Russians (ANONYMOUS, 1954). This upper slope province recalls the Blake Plateau off the southeast coast of the United States, where a similar region next to the shelf has a 1° gradient to depths between 300 and 500 fm (SHEPARD, 1948, pp. 176-177).

Fourth, the existence of an isolated area shoaler than 500 fm centred near 75°N, 158°W, has been established by four sounding lines, only one of which crossed a portion of its summit. The flat-topped nature of the feature as shown in Fig. 2 is an interpretation only. It is proposed that this feature be named Northwind Seahigh after the *U.S.C.G.C. Northwind* which made the southern-most crossing. A broad, flat-bottomed trough which narrows to a steep-walled gap or cleft toward the south separates this spur from the shallow area to the south-west. SHEPARD (1948, p. 105) has applied the term " continental borderland " to similar regions of intermediate depth adjacent to continental shelves.

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Acknowledgments—These studies could not have been carried out without the assistance of a number of persons and organizations. For the 1951 survey the officers and men of the *U.S.S. Burton Island* (AGB-1) are thanked for their co-operation in the field; Dr. WALDO K. LYON of the U.S. Navy Electronics Laboratory and Prof. CLIFFORD A. BARNES of the University of Washington directed the 1951 survey and gave guidance and field assistance. Dr. LYON also provided sounding plots of the 1954 survey as prepared by CHARLES RICHARDSON. For the 1957 work, MAX BREWER, Director of the Arctic Research Laboratory of the University of Alaska, provided laboratory facilities and equipment. M. ALLAN BEAL and JOHN B. SHERMAN III of the Scripps Institution of Oceanography conducted the complementary survey on the *U.S.S. Staten Island*. The writers thank Capt J. A. BRESNAN, Cdr B. M. CHISWELL, Ltjg H. HAUGEN and the other officers and men of the *U.S.C.G.C. Northwind* (WAGB-282) for their enthusiastic support in the 1957 survey; the echo-sounder watch was kept by G. W. DALE, W. C. HAGEN, L. C. PARTAIN and K. C. COOK. ROBERT C. WINSETT drafted the illustrations.

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Contribution of the Scripps Institution of Oceanography of the University of California, New Series No. 985. *U.S. Navy Electronics Contribution No.* 43.

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Deep-Sea Research, 1958, Vol. 5, pp. 7 to 17. Pergamon Press Ltd., London

Essai d'interpretation de quelques formes du terrain sous-marin

D'après les échogrammes de l'expédition suédoise de l'*Albatros*

F. F. Koczy* et M. Burri†

(*Received* 24 *April* 1957)

Abstract—Very accurate echogramms have been compared to structural profiles of the continent. Zones of horsts and grabens, bound by faults scarps have been recognised on the floor of the Indian Ocean. They could be compared, for instance, to accidents of the Rhenan trough. The Atlantic Middle Ridge is a dislocated range. It could well be compared to the great fracturated folds of the Lebanon Ranges. Amongst the atectonics floor profiles, attention has been brought to the big abyssal planes. Many origins are possible. In the case of the Indian Ocean plane, a flow of lava is inferred. The origin of a shallow and small plateau seems to be due to the accumulation of sediments around a still visible rock massif. Waves due to sliding can be observed at the foot of some steep slopes. The three sections of volcanos differ according to the choice of the sections. The advantage and disadvantages of two different nomenclatures are briefly discussed : the descriptive and the genetic approach.

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INTRODUCTION

Le problème des formes du terrain sous-marin a été déjà abondamment traité. Le travail le plus complet sur cette question est certainement le livre de J. Bourcart (1949). Mais la qualité exceptionelle des échogrammes rapportés par l'*Albatros* permet d'envisager cette question sous un angle nouveau. Notre intention n'est pas, en effet, de parler de la topographie générale de l'un ou l'autre des Océans de notre globe, mais de considérer certains points de détail. Les échogrammes de l'expédition suédoise permettent de rétablir des profils fragmentaires à de trés grandes échelles, au 1:20,000 par exemple. L'un de nous (Koczy, 1954) avait dans un court article, déjà tenté d'interpréter certains accidents aux formes caractéristiques.

Après la parution du deuxième travail du même auteur (Koczy, 1956), qui donne les principaux résultats obtenus par l'*Albatros*, il nous a paru intéressant de pousser l'analyse de certains cas particuliers. Pour ce faire nous avons établi quelques profils à de grandes échelles (1:50,000, p. ex.), l'échelle verticale étant la même que l'horizontale, ce qui est plus parlant pour le géologue ou le tectonicien habitué au terrain et aux cartes. La comparison des profils ainsi obtenus avec des profils structuraux est extrêmement intéressante, et elle mérite d'être discutée.

Nous savons bien que comparaison n'est pas raison. Par ailleurs, dans bien des cas, nous ne possédons que des coupes, et nous ne savons pas quel est l'angle que ces coupes font avec l'axe de l'accident rencontré. Dans le cas d'une chaîne sous-marine dont nous connaissons la direction générale, cette cause d'erreur s'élimine partiellement. Cette interprétation de détail est donc limitée à des régions dont nous connaissons déjà les grandes lignes structurales.

Malgré toutes ces causes d'incertitude et d'erreurs, dont nous sommes conscients, cette méthode permet des hypothèses qui sont pour le moins plausibles et qui, pour l'heure, méritent la discution.

Qui dit interprétation, dit recherche des causes. Et ceci nous amène à un essai de classification des formes du terrain, classification qui mérite, elle aussi, la critique et la discution.

FORMES TECTONIQUES

Nous n'avons reconnu, comme formes tectoniques que des failles normales, d'extension, et des plis en larges voûtes plus ou moins fracturées.

Tectonique de failles: horsts et grabens

La region découverte par l'*Albatros*, présentant la tectonique de failles la plus typique, se trouve dans l'Océan Indien, au S-E de l'île de Ceyland. Sur le croquis ci-joint, nous avons reproduit la route de navire et les foyers de secousses sismiques

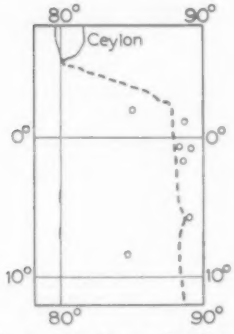

Fig. 1. 0 = foyers de séismes.

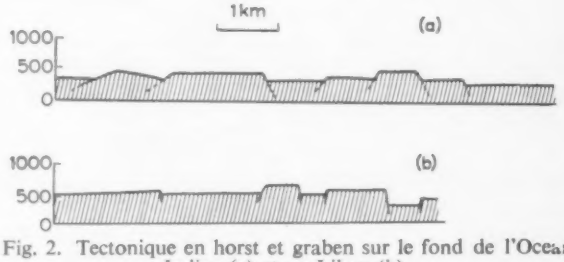

Fig. 2. Tectonique en horst et graben sur le fond de l'Ocean Indien (a) et au Liban (b).

dont nous parlerons plus loin. Les profils de cette region (KOCZY, 1956; pl. XII) montrent une plaine qui s'étend sur plus de 1200 km. Cette plaine n'est pas absolument plane. Il s'agit, en fait, de blocs à inclinaison légèrement variable, séparés par de petits grabens qui soulignent probablement les zones de failles. En plus de ces accidents, des horsts et des grabens de dimension plus réduite sont souvent bien visibles. Le horst le plus important s'élève à près de 2000 m au dessus de cette plaine. Nous donnons une coupe de ce horst au premier profil de la planche qui termine cet article. Le deuxième profil de la planche se situe dans la même région et montre toute une série de horsts et de grabens qui déterminent de plus petites variations d'altitude que dans le cas du premier profil. L'origine tectonique de telles formes est évidente.

Cette zone peut se comparer avec toute autre region presentant une tectonique de failles. On constate, dans la littérature géologique, que l'inclinaison des failles est, le plus souvent, assez imprécise, leur tracé étant fréquemment masqué par des formations quaternaires. Les deux coupes comparatives que nous donnons ici sont à la même échelle (Fig. 2). La première est un profil du fond de l'Océan Indien,

Nota Dans les profils que nous avons retabli à l'échelle normale (verticale = horizontale) nous avons indiqué les altitudes à partir d'une ligne 0 arbitraire, placée sous le profil, ceci afin de simplifier les comparaisons avec les coupes prises sur le continent. Les autres profils, repris directement du travail de KOCZY (1956), et qui illustrent des phénomènes de détail, ont comme échelle verticale les profondeurs vraies à partir du niveau de la mer.

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c'est un fragment du profil XII-11 de KOCZY (1956). La deuxième est un profil structural dessiné sur la surface du jurassique, à travers la colline d'Abeih (Liban, dans DUBERTRET, 1950).

Il nous a même été possible de dresser des profils à des échelles plus précises (env.: 1:25,000). La comparaison des quatre profils de la Fig. 3 montre des resemblances frappantes. Les deux premiers sont donc des profils du fond de l'Océan Indien, en

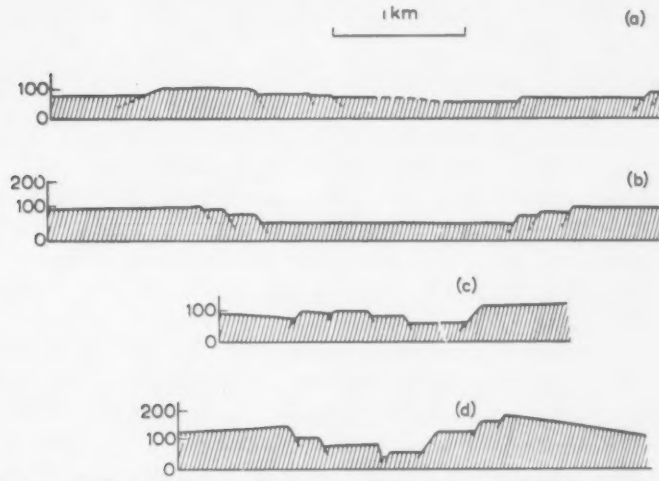

Fig. 3. Profils structuraux à travers des grabens sous l'Océan Indien (a) (b), Fosse du Rhin (c), et le Plateau du New Mexico (d).

horsts et grabens, soit en graben simple. Le troisième profil est un fragment d'une coupe structurale dessinée sur les " couches rouges " dans le graben du Rhin (région de Pechelbron, SCHNAEBELE, 1948). Ici les failles sont bien connues, car elles ont été recoupées par de nombreuses galeries. Le dernier profil est également une coupe de détail dans un petit graben des plateaux de l'W des Etats Unis (New Mexico, FERGUSSON, 1927) La bonne qualité des affleurements permet ici aussi une connaissance exacte de l'inclinaison des failles.

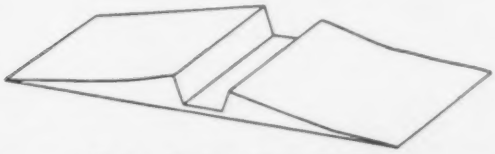

Fig. 4. Graben d'après H. CLOOS.

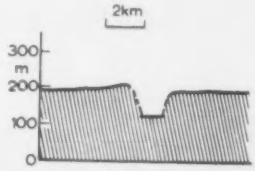

Fig. 5. Détail d'un graben. (KOCZY XII — B).

A propos de cette tectonique, il est necessaire de faire quelques remarques. Les failles que nous avons observées présentent des inclinaisons qui concordent parfaitement avec les donnees geometriques étudiees sur le continent. Leur inclinaison varie assez peu autour de 45°. CLOOS (1939), dans un article qui est capital pour la compréhension de la tectonique de failles, a donné toutes les caracteristiques geometriques

des grabens. Il montre, dans ceux qu'il définit comme " antithétiques," que les grabens présentent une surélévation dont les flancs externes montrent une concavité tournée vers le haut (Fig. 4). C'est bien ce que l'on observe dans l'Océan Indien. Comme les pentes sont extrêmement faibles, cette concavité n'est pas visible sur des profils dont l'échelle verticale est la même que l'horizontale. Mais sur les échogrammes, oú l'échelle verticale est exagérée (env. 40 fois) cette convavité se voit nettement. Ceci est bien caractéristique sur la Fig. 5. Presque tous les grabens de cette rêgion ou bien montrent ce phénomène, ou bien possèdent une de leurs lèvres à une altitude différente de l'autre.

EWING, HEEZEN, *et al*, (1953) donnent des profils à travers un canyon de l'Atlantique Nord où, également, les deux bords sont à des altitudes différentes.

Ces quelques remarques nous semblent nécéssaires, car ces petits fossés de l'Océan Indien ont été interprétés par DIETZ (1953) comme un phénomène d'érosion dû aux courants de turbidité. Or, en fonction de ce que nous venons de dire, cette hypothèse nous semble fort peu probable. De plus, l'analyse récente d'une carotte de 7 m de long (non publié) prélevée dans cette région, n'a montré aucune sédimentation par courant de turbidité comparable à la sédimentation décrite par ERICSON, EWING, *et al.* (1955) dans l'Océan Atlantique.

Remarquons en terminant, que GUTENBERG et RICHTER (1950) placent dans cette région de l'Océan Indien plusieurs épicentres de secousses sismiques superficielles dont l'origine, au point de vue géologique, est inconnue. Il est tentant d'admettre que ces failles jouent encore faiblement, et qu'elles sont à l'origine de ces secousses superficielles. Ces épicentres sont marqués par de petits ronds sur la carte qui introduit ce chapître.

Chaines fracturées

La chaîne Médio-Atlantique présente une structure de surélévations coupées par de grandes failles. Les profils qui sont donnés sur la planche finale (profils 3, 4 et 5)

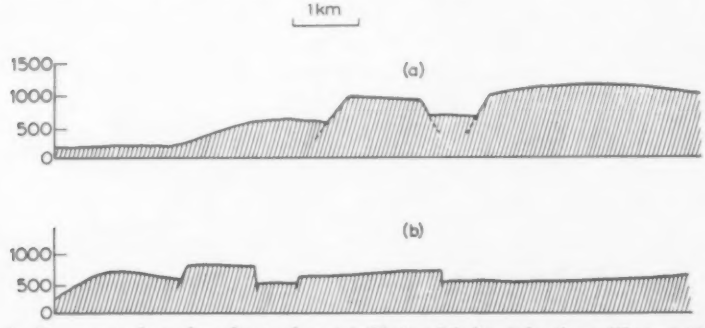

Fig. 6. Structures de voûtes fracturées: (a) Chaîne Medio-Atlantique (KOCZY 11-7); (b) Chaîne du Liban.

montrent quelques-unes de ces voûtes qui atteignent l'altitude de 2000 m par rapport à la région avoisinante. Des failles gigantesques, inclinées de 45 à 60° fracturent ces voûtes, produisant de brusques variations d'altitude, dépassant parfois 1500 m.

La chaîne la plus connue qui présente des coupes structurales voisines des profils obtenus sur la chaîne Médio-Atlantique, est la chaîne libanaise. Il est à remarquer

que, du fait que nous connaissons assez exactement la direction générale de la chaîne, nous savons que les profils dessinés par l'*Albatros* sont sensiblement perpendiculaires aux accidents rencontrés.

Nous donnons ici (Fig. 6) deux profils que l'on peut comparer. Le premier se trouve dans la chaîne Médio-Atlantique, le suivant est une coupe structurale dessinée sur le sommet du Kimméridgien, dans la partie Sud de la chaîne libanaise. (HEYBROEK, 1942).

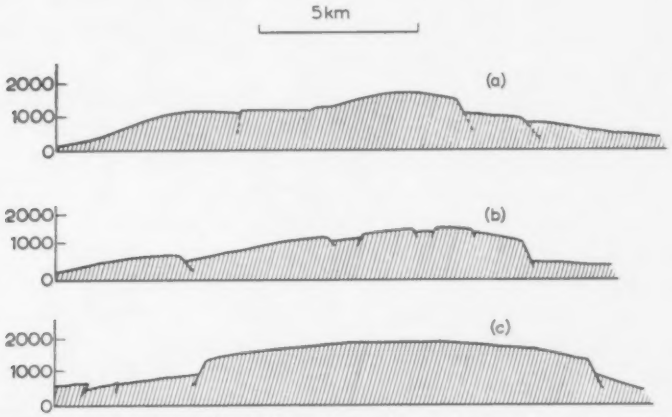

Fig. 7. Structures en voûtes fracturées: (a) Est du Pacifique (KOCZY LV – 2); (b) Chaîne du Liban – Sir Ed Danié; (c) Chaîne du Liban - Zahlé.

Trois autres coupes (Fig. 7) que l'on peut comparer, montrent les mêmes ressemblances. La première est un accident du fond du Pacifique, entre l'Amérique et les Iles Galapagos. Il présente les mêmes caractéristiques que les accidents médio-atlantiques (voir les profils de la planche). Les mêmes structures se retrouvent dans les coupes structurales libanaises des feuilles de Sir Ed Danié, pour le profil 2, et Zahlé, pour le profil 3 (DUBERTRET, 1951; 1953).

La chaîne Médio-Atlantique est le siège de très nombreuses secousses sismiques, ainsi que le montrent les cartes de GUTENBERG et RICHTER (1950). Il n'est pas impossible que cette fracturation de la chaîne se poursuive encore actuellement.

Les descriptions de l'Atlantique données par TOLSTOY et EWING (1949) de même que les hypothèses de CLOOS (1939) sur l'origine des Açores ne sont pas en opposition avec une telle fracturation. Ce que nous savons sur la composition minéralogique de cette chaîne non plus: des coulées volcaniques accompagnent souvent les zones fracturées (volcans des grabens est-africains).

FORMES NON TECTONIQUES

Dans ce paragraphe, nous donnons quelques remarques sur des formes qui sont apparement dues à la sédimentation. Il est évident que la comparaison avec des phénomènes terrestres est ici difficile, souvent même impossible.

Plaines abyssales

Dans un article intéressant, HEEZEN, EWING et ERICSON (1955) résument les

différentes hypothèses émises sur l'origine des plaines abyssales. Celles-ci pourraient être:

(1) des régions atectoniques;

(2) des zones d'érosion subaérienne;

(3) des plaines de laves;

(4) des zones de sédimentation prolongée;

(5) des zones où se concentrent des sédiments très fins apportès par les courants sous-marins. Et ces auteurs proposent une nouvelle interprétation, celle de la sédimentation par les courants de turbidité.

Peut-être que toutes ces explications sont justes, mais chacune dans un cas particulier. Il est en effet presque hors de doute que la plaine abyssale au Sud de Terre-Neuve, que ces auteurs décrivent, est due à une sédimentation de courants de turbidité. Mais cette explication s'applique t'elle à toutes les plaines abyssales ?

Revenons à notre grande plaine de l'Océan Indien. Elle s'étend, sur des centaines de kilométres, au Sud du Golfe de Bengale. L'*Albatros* en a rapporté une coupe très complète (Koczy, 1956, pl. XII). Rappelons tout d'abord que cette plaine montre de faibles accidents. Si, comme nous l'avons fait sur ce dessin (Fig. 8), l'on amplifie fortement l'échelle verticale (env. 100 fois), il ressort que cette plaine est constituée

Fig. 8. Fragment des plaines abyssales de l'Océan Indien L'échelle verticale est fortement exagérée (Koczy XII).

de larges blocs d'inclinaison lègèrement variable. Ces blocs sont séparés par de petits fossés qui soulignent probablement les zones de failles. Or, dans cette partie de l'Océan Indien, au cours des opérations de carottage, de nombreux appareils se brisèrent sur un fond dur, sous quelques décimètres de sédiments. Il semble donc plus logique d'attribuer à cette plaine une origine volcanique: ce serait une grande plaine de lave en voie de fracturation.

Dans d'autres cas, il est peu douteux qu'une longue sédimentation soit à l'origine des plaines abyssales. La preuve est impossible à donner uniquement sur des formes du fond, des études sismiques, ou, de préférence, des carottages pourraient trancher la question. L'existence de telles plaines est admise par Dietz, Menard et Hamilton (1954) entre les Etats Unis et les Iles Hawaï. Une longe sédimentation a pour effet de masquer la topographie préexistante, d'autant plus que les courants sous-marins favorisent la sédimentation dans les dépressions et la ralentissent sur les élévations. Dans des régions accidentées, certaines dépressions possèdent un fond plat qui contraste fortement avec la topographie avoisinante. Ce phénomène est fréquent sur la chaîne de Carlsberg, entre les Indes et les Seychelles.

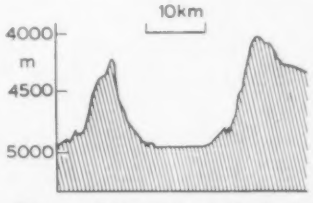

Fig. 9. Dépression à fond plat (Koczy XXI – 24).

(Voir les profils XIII – 7, 8 et 9, de KOCZY, 1956). La figure que nous donnons pour illustrer de phénomène est extraite d'un profil au large de la Guyanne (Fig. 9). L'échelle verticale est amplifiée de 40 fois environ.

On comprendrait mal un tel phénomène sans supposer une sedimentation prolongée, qui tend à combler les dépressions. Que l'on prolonge ce processus assez longtemps, et toute topographie disparaîtra. Seuls des carottages permettront de savoir quelle sorte de sédiments comblent ces dépressions.

Plateaux

Un cas intéressant rapporté par l'*Albatros* est celui d'un petit plateau, situé à une cinquantaine de kilomètres du Cap Gardafoui, sur le plateau continental de l'Afrique (Fig. 10).

A 80 m de profondeur, long de huit kilomètres, il domine de 120 m la région avoisinante; ses bords sont très raides, presque verticaux. Le dessin que nous en reproduisons est la copie de l'échogramme, donc avec une échelle verticale amplifiée de env. 40 fois. Au centre de la surface plane se trouve une petite surélévation qui a donné un triple écho trés net. Il semble donc que l'on ait un rocher entouré d'une zone sédimentaire plus tendre, large de 4 km de part et d'autre de ce bloc rocheux.

La manière la plus simple de comprendre une telle forme est de supposer qu'il y avait là un rocher autour duquel les sédiments se sont accumulés, sous l'influence des courants. A une si faible profondeur, bien des mouvements de l'eau se font sentir:

(1) courants permanents;
(2) courants des marées;
(3) courants dus à la houle et aux vagues.

A la bordure du plateau, des éboulements se produisent, ce qui expliquerait les pentes si raides.

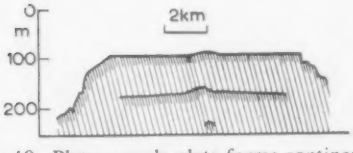

Fig. 10. Plateau sur la plate-forme continentale (KOCZY XIV – A).

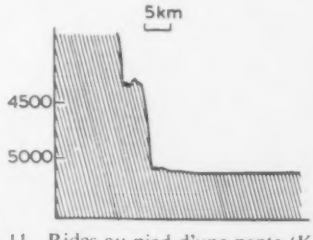

Fig. 11. Rides au pied d'une pente (KOCZY XIV – 4; échelle vert. x 40).

Formes de glissement

Au pied de certaines pentes raides, sur quelques centaines de mètres, deux ou trois rides se succèdent, avant une zone plane totalement dépourvue d'accidents. Un des cas les plus typiques est reproduit dans cette figure (Fig. 11), à la base d'une pente d'un accident entièrement sous marin. Ces rides rappellent celles que l'on observe fréquemment sur le terrain, au front des glissements de terrain, surtout lorsqu'ils ont été stoppés par une pente d'inclinaison décroissante. Le même phénomène s'observe aussi, à une plus petite échelle, lors du glissement de masses de neige. Lorsque la neige est lourde et gorgée d'eau, de grosses masses peuvent se mettre en mouvement, avec une certaine lenteur, parfois imperceptiblement. A l'avant de la masse glissante,

se forment des rides angalogues à celles de la base de ces pentes sous-marines. Il est évidemment impossible de donner des coupes de détail d'un glissement de terrain ou de neige, l'échelle de ces phénomènes étant assez différente de celle des phénomènes sous-marins.

VOLCANS

Les volcans appartiennent à une catégorie d'accidents qui ne sont ni tectoniques, ni sédimentaires, au sens restreint où nous avons utilisé ces deux termes.

Les échogrammes précis de l'expédition suédoise ne nous apprennent pas grand chose de nouveau sur les volcans. Les terrasses successives, que l'on remarque bien sur ces dessins, avaient déjà été signalées par le *Snellius* puis reprise par KOCZY. Mais il nous semble intéressant de signaler que la route du bateau ne passe pas souvent au dessus du sommet du volcan. Les trois profils de la Fig. 12 sont choisis dans l'W du Pacifique ou l'E de l'Océan Indien. L'origine volcanique de ces accidents est attestée par la présence d'îles volcaniques voisines, et par la situation de ces accidents dans des zones à topographie plane.

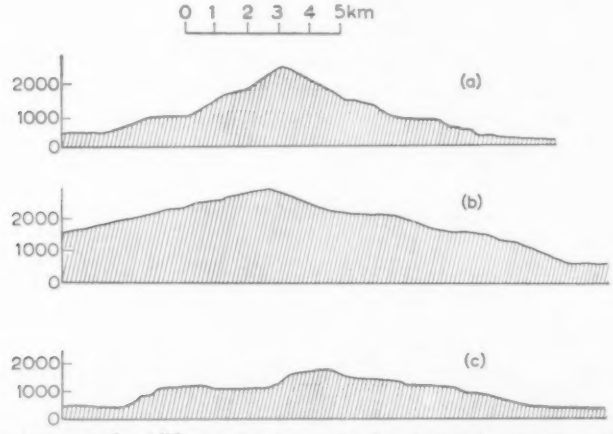

Fig. 12. Coupes à travers des édifices volcaniques: (a) Sur de l'Océan Pacifique (KOCZY VI – 12); (b) E de l'Océan Indien (KOCZY XI – 7); (c) N de l'Australie (KOCZY IX – 12).

La premiére de ces coupes semble bien passer, soit au sommet même de l'édifice volcanique, soit dans son viosinage immédiat. L'allure générale rappelle bien celle des volcans que nous connaissons sur le continent. Le deuxième profil coupe le flanc du volcan: les pentes sont beaucoup plus faibles. Quant à la dernière coupe, elle semble passer assez loin du point sommital. Il ext important de ne pas confondre cette structure en terrasses très plates avec une structure en horst. Il serait impossible de distinguer ces deux structures sur les seules données d'un profil du fond. Seule une connaissance de la région avoisinante autorise une meilleure approximation.

CONCLUSIONS

Il est aisé de voir les possibilitiés d'interpretation que présentent des échogrammes de très bonne qualité. Certes, les failles sont le type d'accidents qui est le plus accessible à cette méthode. Mais les grandes zones de fracturation ne sont-elles pas un des phénomènes dont la connaissance est capitale pour la compréhension de la structure

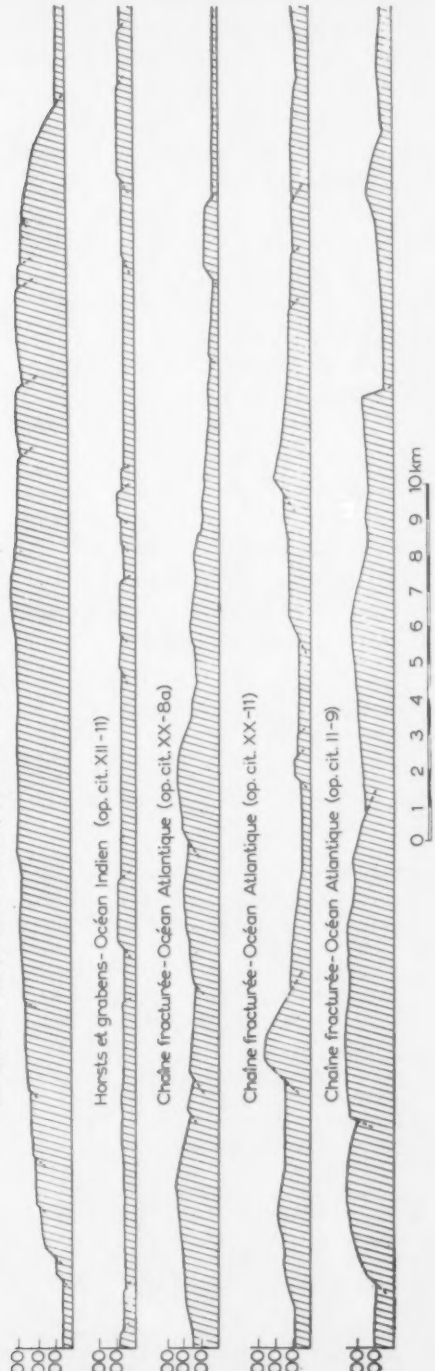
Structure en horst-Océan Indien (redessiné de KOCZY 1956: XII - 4)
Horsts et grabens - Océan Indien (op. cit. XII - 11)
Chaîne fracturée - Océan Atlantique (op. cit. XX - 8a)
Chaîne fracturée - Océan Atlantique (op. cit. XX - 11)
Chaîne fracturée - Océan Atlantique (op. cit. 11 - 9)
1500
1000
500
0 1 2 3 4 5 6 7 8 9 10km

Fig. 13. Planche.
Structure en horst – Océan Indien redessiné de Koczy 1956: x 11-4
Horsts et grabens – Océan Indien op. cit XII – 11.
Chaîne fracturée – Océan Atlantique op. cit. XX – 8(a).
Chaîne fracturée – Océan Atlantique op. cit. XX – 11.
Chaîne fracturée – Océan Atlantique op. cit. 11– 9.

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de la planète? Des zones de fracturation sont déjà connues dans L'Océan Pacifique, où elles furent décrites par DIETZ, MENARD et HAMILTON (1954). La zone de fracturation de l'Océan Indien est sans doute d'importance topographique moins grande, mais sa signification structurale peut-être tout aussi intéressante. Il reste dans les Océans bien des zones inconnues, et où il existe peut-être des failles que seuls des échogrammes extrèmement précis permettront de découvrir. Dans ce but, les appareils utilisés par l'*Albatros* devraient être plus généralement utilisés.

Pour les questions de nomenclature des reliefs des fonds océaniques, il existe deux tendances, qui toutes deux, présentent des avantages et des inconvénients. L'une est purement descriptive; elle est représenteé par un Comité International (WISEMAN et OVEY 1953; 1955). L'autre tendance essaie une classification logique; elle fut défendue par BOURCART (1955) et par KOCZY (1954). La première tendance risque de rester un peu confuse, utilisant le même nom pour des accidents d'origine différente. BOURCART a montré que certaines définitions (p. ex. le plateau continental) ne s'appliquaient pas dans toutes les mers. Le géologue a instinctivement tendance à utiliser, sinon une classification, du moins des termes génétiques: le seul probleme qui l'intéresse est justement celui de l'origine des formes. Une telle classification présente le désavantage d'être fréquemment sujette à changements, au fur et à mesure du progrès des méthodes d'investigation. Mais des échogrammes très prècis permettent, dans bien des cas, de lever le doute des origines de certaines formes. Il faut rester très prudent, surtout tant que des recherches à plus grande échelle ne permettent pas de reconstructions a trois dimensions.

Remerciements—Qu'il nous soit permis, en terminant, de remercier MM. les Professeurs H. PETTERSON et B. KULLENBERG, qui nous ont permis de consacrer, à Göteborg, une partie de notre temps à cette recherche, et M. le Professeur H. BADOUX, de l'Université de Lausanne, qui a su nous faire profiter de ses critiques et de sa grande culture géologique.

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Deep-Sea Research, 1958, Vol. 5, pp. 18 to 28. Pergamon Press Ltd., London

The morphology of Kermadec and Hikurangi trenches*

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(*Received* 4 *November* 1957)

Abstract—The Kermadec Trench extends 700 miles from 26°S towards New Zealand. Its steep sides with major benches, narrow floor and greater depth separate the Kermadec Trench from the slightly offset, broader and shallower Hikurangi Trench off the east coast of New Zealand. Hikurangi Trench has small-scale benching along its axial depression.

Benched sides are also found in Tonga Trench and in other Pacific trenches. The benches are ascribed to superficial normal faulting on the flanks of a major deep-seated crustal depression.

New soundings obtained in the S.W. Pacific by explosion sounding equipment are discussed and the instrumentation described.

New names, Hikurangi Trench, Colville Ridge, and Havre Trough are proposed for bathymetric features not previously clearly defined.

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INTRODUCTION

A BATHYMETRIC chart of the area from Wolverine Shoals to New Zealand has been constructed from soundings on existing Admiralty and U.S. charts and from additional echo-sounding traverses from the records of the N.Z. Oceanographic Institute. (Fig. 1) Soundings across the Kermadec Trench obtained by *H.D.M.S. Galathea* 1952, *H.M.S. Challenger* 1951, *Francis Garnier* 1949-50, have been used, in addition to soundings taken from *H.M.N.Z.S. Lachlan*, by means of explosion sounding equipment (see Appendix). All the foregoing trench soundings have been corrected for variations in sound velocity.

Control of isobaths defining the Hikurangi Trench comes mainly from explosion soundings by *Lachlan* and by the Institute's research vessel *R.N.Z.F.A. Tui*, and from conventional echo-soundings by *Lachlan* and *R.R.S. Discovery II.*

BATHYMETRY OF THE CHART AREA

Kermadec Trench. The northern and southern limits of the Kermadec Trench have been defined by WISEMAN and OVEY (1955), as 26°S and 36°S : these limits coincide with the extent of sea floor 4000 fathoms or more deep. The bathymetry shows that the trench form continues southward along a prolongation of the axis to 37° 30′S where the trench-floor lies in 2250 fm. Though from 36° to 37° 30′S the difference in elevation between the trench floor and oceanic depths of the S.W. Pacific Basin to the east, lessens progressively, it seems advisable to extend the southern limit of the Kermadec Trench to 37° 30′S.

The six hundred mile length of trench floor (between 26° and 36°S) deeper than 4000 fm has a maximum width at this isobath of 45 miles. Soundings of 5000 fm and more have been secured in three discrete areas centred on latitudes 28° 30′, 30° 30′ and 32°S. The trench floor appears as a series of depressions below 5000 fm; the continuity of the trench is best expressed by the 4000 fm isobath. From 32° to 33°S the floor deeper than 4000 fm is irregular. This appearance may in part be due to the use of all available soundings some of which may be in error or mis-

placed ; nevertheless the extent of the irregularity suggests it is real. The greatest depth sounded in the trench is that by *Galathea* in 1952 — 5465 fm in 31° 53′S 177° 05′W – in the area of irregular bottom.

Kermadec Ridge. On its western flank the trench is bounded by the Kermadec Ridge from 27° to 35° 30′S. The ridge crest lies at less than 1000 fm and mostly at depths less than 750 fm. From the crest rise banks (such as Star of Bengal Bank, 32° 30′S), rocky islets such as Havre Rock and Curtis and Macauley Islands, and Raoul Island towards the north end of the ridge. The Kermadec islands are predominantly andesitic volcanics and minor volcanic activity persists on Macauley and Raoul Islands, the latter experiencing a small eruption in 1872.

Havre Trough. West of and paralleling the Kermadec Ridge is a broad depression of the sea-floor. At its southern end this trough terminates against the New Zealand shelf in a number of tectonic depressions, one of which has been described by FLEMING (1952) as White Island Trench. FLEMING also applied this name to the broad trough extending northward. Subsequent sounding has revealed the existence of three major indentations of the continental slope at the shoreward end and it is advisable to limit the name White Island Trench to one of these — the well-defined linear canyon-like feature adjacent to the volcano White Island. For the trough approximately 70 miles wide, extending from the New Zealand Coast to 26°S the name Havre Trough is suggested (from Havre Rock to the east of the mid-point of the trough). The trough is discontinuous. It is more than 1500 fm deep in the south with a maximum depth in lat. 32° 45′S of over 2000 fm ; between 30° and 32°S the trough is ill-defined ; the northern portion is more than 1250 fm deep with a maximum of over 1500 fm (lat. 27° 30′S).

Colville Ridge, South Fiji Ridge. Further west again, two ridges also trending north-north-east form the western margin of Havre Trough. The South Fiji Ridge extends through the Wolverine Shoals (lat. 25° 30′S) to lat. 30°S. Much of its crest is in less than 500 fm. From 32°S to the New Zealand coast Colville Ridge, deeper and with less relief continues the line of South Fiji Ridge. The crest of Colville Ridge lies at depths of 1000-1250 fm. (The suggested name comes from Cape Colville at the southern end of the ridge.)

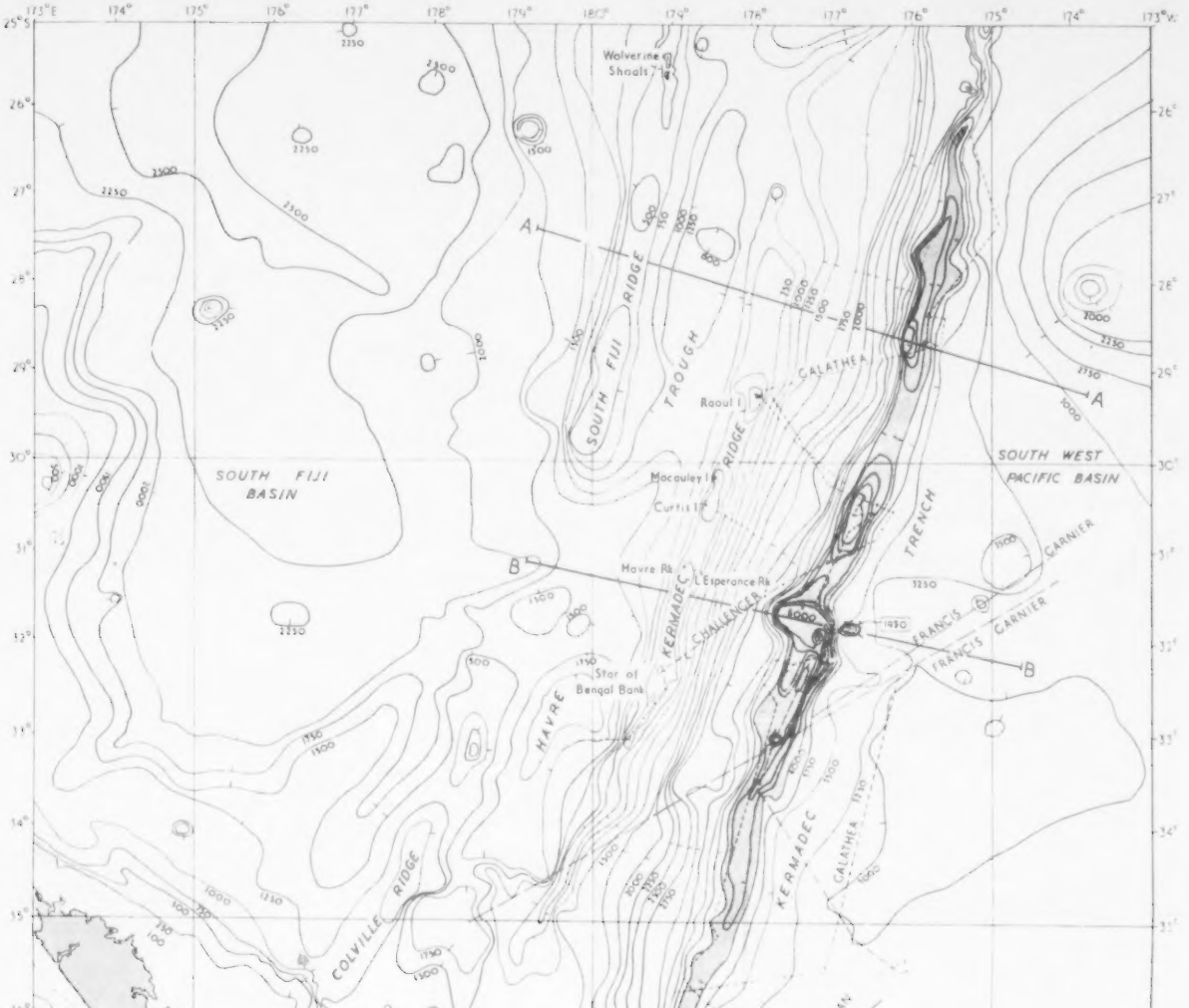
West of the ridges and sparsely sounded (as are both ridges and trough) lies the South Fiji Basin, its floor in depths of 2000-2500 fm.

The eastern wall of the Kermadec Trench rises steeply to the floor of the S.W. Pacific basin in 3250 fm. Seamounts, (identified from single soundings, and up to the present unsurveyed) occur along the axis and eastern margin of the trench.

The alignment, relief and broad features of the Kermadec Trench are similar to those of the Tonga Trench described by RAITT, FISHER and MASON (1955). The marked discontinuity between South Fiji Ridge and Colville Ridge and between Northern and Southern portions of Havre Trough is not reflected in any feature of Kermadec Ridge though the greatest depth in the Kermadec Trench and indications of sea-mounts lie on the same, roughly east–west line.

Hikurangi Trench. There has been hitherto, considerable uncertainty about the status of the strip of deep ocean floor immediately off the eastern coast of New Zealand from East Cape to Cook Strait. This has arisen from the approximate continuity of the axes of this feature and of the Kermadec Trench, from the lack of definitive soundings on its eastern margin and from the consistently lesser depth

Fig. 1. Bathymetry of the Kermadec Trench Area.


SOUTH FIJI BASIN
SOUTH WEST PACIFIC BASIN
SOUTH FIJI RIDGE
TROUGH
CALATHEA
RIDGE
TRENCH
KERMADEC
CHALLENGER
FRANCIS GARNIER
HAVRE
COLVILLE RIDGE
Wolverine Shoals
Raoul I.
Macauley I.
Curtis I.
Havre Rk.
L'Esperance Rk.
Star of Bengal Bank
A
B
173°E
174°
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180°
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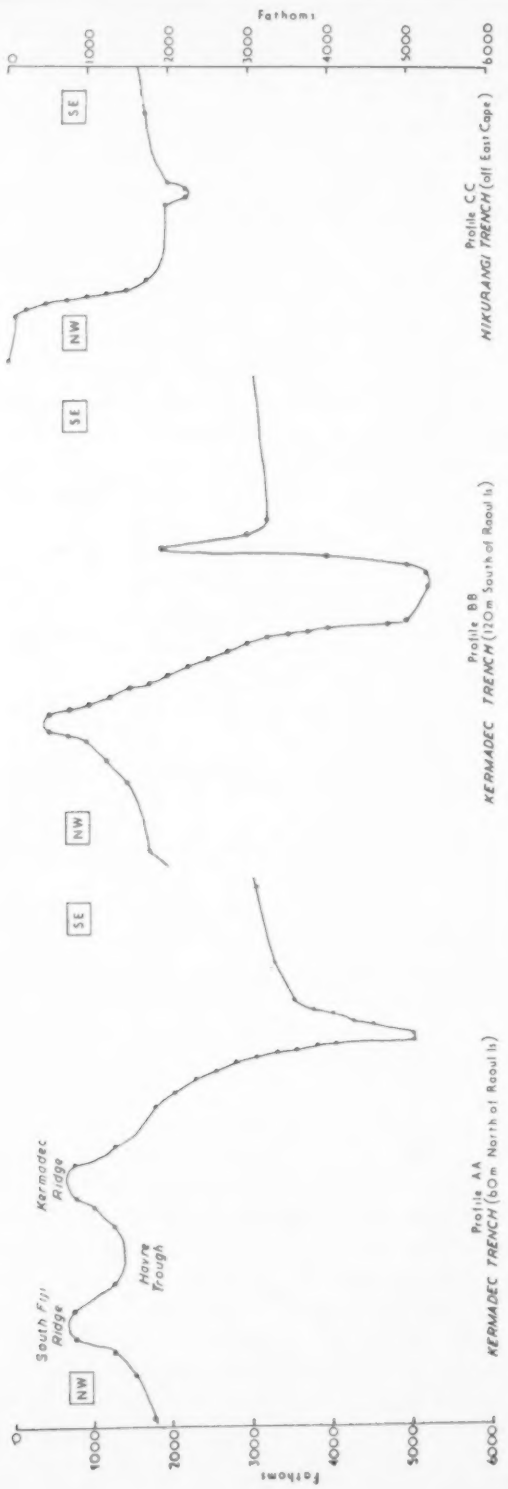

Fig. 2. Generalized transverse profiles constructed from the bathymetric chart. Vertical scale exaggerated x 50.

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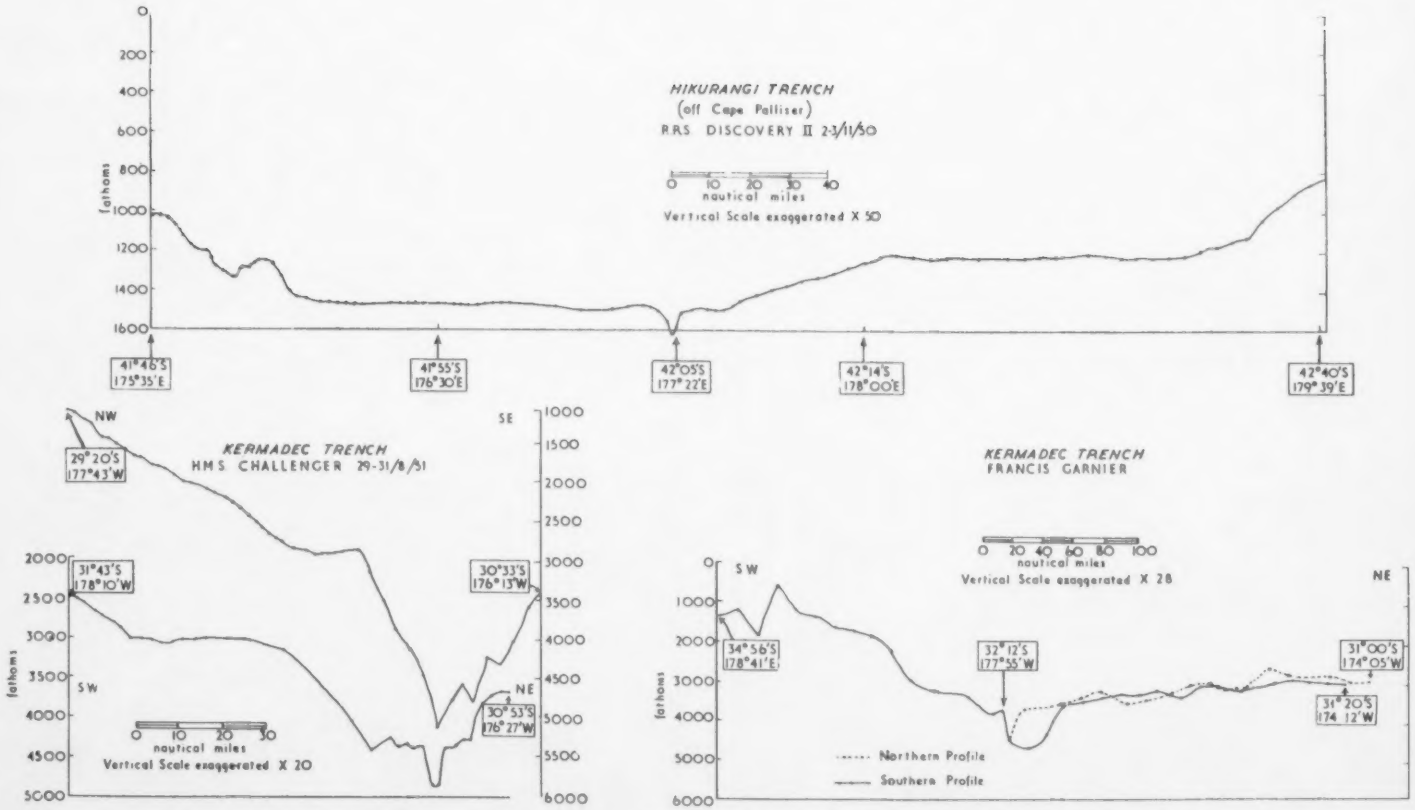

Fig. 3. Trench profiles from sounding traverses. The *Discovery II* profile is from half-hourly corrected soundings.

here (less than 2000 fm) of the trench floor compared with the Kermadec Trench.

The feature warrants recognition as a minor oceanic trench, for although its form is somewhat diffuse at the northern end off East Cape, yet from 40° to 42° 30′S the width decreases and the trench form is better defined. From 37° 30′S the trench extends 300 miles southward, with an average width of 60 miles. Its floor shoals evenly from 2000 to 1500 fm in this distance. At its northern end the trench axis is offset 50 miles eastward from that of the Kermadec Trench. Except where the trench abuts against the Chatham Rise in the south, its eastward margin is defined by a decrease in depth of approximately 250 fm. The western flank, however, rises abruptly to the New Zealand land mass, forming the continental slope of the North Island east coast. The trench axis is 50 miles offshore in the south, diverging to 90 miles offshore off East Cape. The name Hikurangi Trench* is proposed from a prominent and well known mountain of that name near East Cape.

The S.W. Pacific basin east of the trench is very inadequately sounded and critical consideration of the morphology, particularly of the eastern flank of the trench requires more data than is at present available.

TRENCH PROFILES

Some feature of the Kermadec Trench are illustrated by profiles AA and BB (Figs. 1 and 2) constructed from the chart, and the pairs of profiles from soundings by *Challenger* and *Francis Garnier* (Fig. 3). The ocean floor to the east lies at approximately 3250 fm and the transition from ocean floor to trench is sharp. Both chart and profiles demonstrate the existence of a bench averaging 10 miles in width, at the same average depth, 3250 fm, along the western slopes of the trench. From bench and ocean floor, the trench sides descend steeply, flattening once more at 4000 to

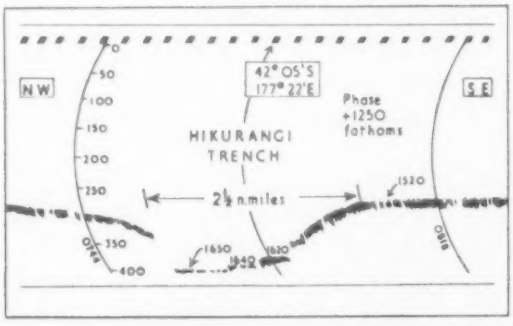

Fig. 4. Central depression in Hikurangi Trench. From echo soundings (uncorrected) by *R.R.S. Discovery II.*

4500 fm with fragmentary benches on one or both sides at this level. Several profiles show that below this depth the sides in places drop steeply again to form a narrow innermost trench averaging five miles in width. The western slopes below 3250 fm are slightly more steep than the eastern.

Two profiles across Hikurangi Trench have been constructed, profile CC (Figs. 1 and 2) from the bathymetry, and that from soundings by *Discovery II* (Fig. 3). In

*Suggested by Mr. G. L. ADKIN.

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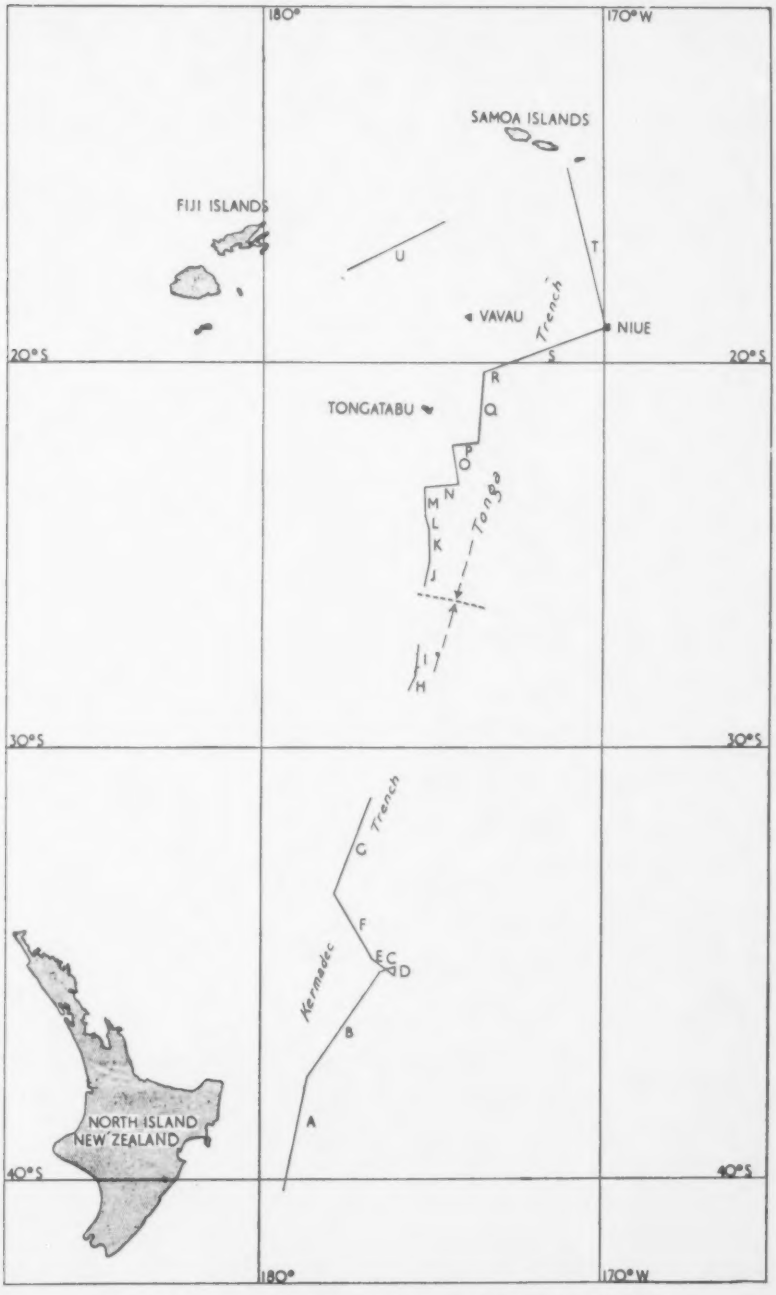

Fig. 5. Location of lines of soundings made from *Lachlan* 1955.

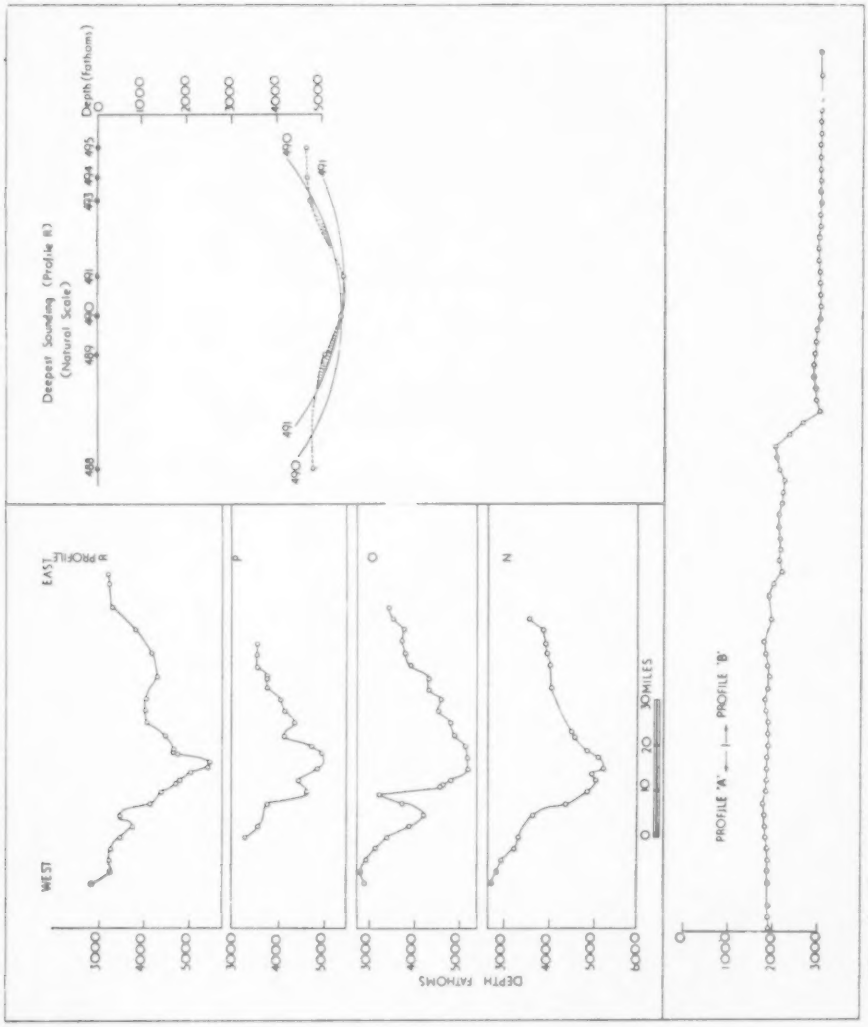

Fig. 6. Kermadec and Tonga profiles from explosion soundings from *H.M.N.Z.S. Lachlan* 1955.

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the axial portion of the trench, relatively steep sided depressions drop 150-250 fm below the broad trench floor at 1500-2000 fm. Fig. 4 illustrates this median depression; here, towards the southern end of the trench, the floor descends from 1520 fm in the east in five steps to 1650 fm over a distance of 2 miles. The western slope is steeper, the trench floor and the surfaces of the benches are level. The floor is just under ¾ mile wide.

ORIGIN OF TRENCH-WALL BENCHES

The most striking feature of the Kermadec Trench, apart from its linearity, is the benched nature of the walls. On a smaller scale the same terracing is found in the axial depression in the Hikurangi Trench.

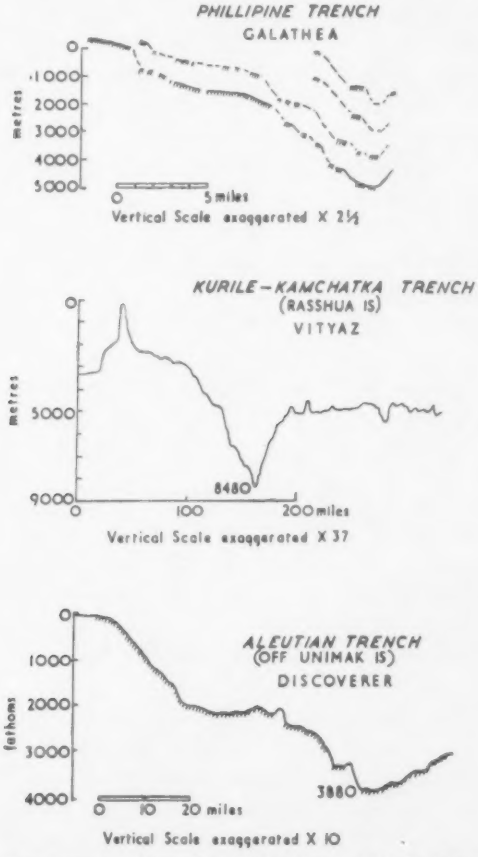

Fig. 7. Transverse profiles of the Phillipine and Kurile-Kamchatka Trenches (after UDINTSEV, 1955) and of the Aleutian Trench (after MURRAY, 1945).

The 3250 and 4000–4500 fm benches occur also in the Tonga Trench as the profiles (Figs. 5 and 6) show. The existence of similar benches on the sides of deep sea trenches has been commented on by a number of authors ; in particular, UDINTSEV (1955) draws attention to the general occurrence of morphological benches on trench

sides, using examples from the Kurile-Kamchatka, Marianas, Philippine and Aleutian trenches (Fig. 7).

The circum – Pacific trenches are commonly considered to be of compressional origin. However, WORZEL and SHURBET (1955) reasoning from the reduced crustal thickness beneath oceanic trenches have suggested a tensional origin. Whether the deep-seated cause of trench formation be compressional or tensional a linear depression in the superficial crustal layers is produced, generally at the boundary of " oceanic " crust.

The surface of the depression is typically benched. It is reasonable to assume that the bench surfaces where resting at high angles (UDINTSEV, 1955) are immediately underlain by resistant rock ; bench surfaces at low angles could be either resistant rock or surfaces of accumulation of sediment, held up by hard-rock at the downslope margins of the benches.

The steeper and assumably hard-rock benches and the level benches if hard-rock floored are analogous to the surfaces of down-faulted strips of normal-faulted graben structure. If the near-level bench surfaces are " perched " sediment accumulations, these could equally result from similar normal faulted strips with back-tilted surfaces or from a synclinorium-type fold structure.

Thus the probability is that the benches as morphological features are the surface expression of at least superficial normal faulting above the depression. The benches possess a crude bilateral symmetry.

This hypothesis does not clarify the question of compressional or tensional origin, for though the superficial graben-like features would be more directly related to a deep-seated tension structure, they could equally arise on the flanks of a major compressional down-fold.

TRENCH SEDIMENTS

The quantity of sediment available in the Kermadec Trench area is likely to be small : the bulk of this is primary volcanics, the products of shore-line erosion of the volcanics of the Kermadec Ridge, organic remains, and windblown and cosmic particles. However, if normal faulting controls the surface features of the trench walls then a significant quantity of fault-produced debris will be available on either side of the trench.

Hikurangi Trench, adjacent to the New Zealand coast which is a ready source of terrestrial sediment has a broad near-level floor with only a narrow, benched and shallow trench-form along its axis. It is likely that the extensive level floor is directly associated with the availability of sediment : the horizontal surfaces of the axial benches lend support to the relationship. Seismic refraction studies of the trench floor have not as yet been carried out.

Acknowledgments—The authors thank Captain G. S. RITCHIE and the New Zealand Naval Board for co-operation in initial trials with the explosion sounding equipment ; the Hydrographer of the Navy for the use of soundings by *H.M.S. Challenger* ; Dr. H. F. P. HERDMAN and the United Kingdom National Institute of Oceanography for use of the *Discovery II* soundings ; Mr. C. T. WEBB for preparation of the illustrations.

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APPENDIX

Recent deep soundings in the south-west Pacific

A number of the soundings on which the bathymetry of Kermadec and Hikurangi Trenches is based were obtained by explosion-sounding equipment, the development and initial trials of which are described below. Locations of the initial series of soundings are shown on Fig. 5, while the results of soundings are deposited with the Hydrographer, Admiralty and in the records of the New Zealand Oceanographic Institute.

Development

For the 1955 survey cruise of *H.M.N.Z.S Lachlan* north of New Zealand the then Commanding Officer (Captain G. S. RITCHIE, R.N.) requested the Department of Scientific and Industrial Research to investigate the possibility of enabling the ship to sound depths up to 6000 fm, while cruising at normal speeds. A portable interchangeable deep-sounding unit has been developed which can be transferred with little installation effort to any ship fitted with normal echo-sounder.

The usual source of the signal in an echo-sounding machine is a magnetostrictive device of high frequency, but for very deep soundings in unfavourable conditions there is often insufficient energy in the pulse to produce a readable echo at the ship. In such cases a much higher energy source is required and explosives have been used (FISHER, 1954). Such an explosive source using the ships echo-sounding transducer as detector and simple amplification and recording techniques have enabled successful soundings to be made by *Lachlan* under poor conditions in water of depth up to 5500 fm, and have since been successfully used from *Tui* and other New Zealand naval vessels.

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The equipment

The *Lachlan's* deep echo-sounder is a modified asdic ranger. The transducer, which both transmits and receives the high-frequency signal, is horizontally trained and a vertical sounding is made possible by a suitable deflecting plate placed just in front of the transducer. This arrangement has certain disadvantages for vertical sounding but for various reasons it was decided to use the ship's transducer as the detector system in the present series of soundings. The energy source for the soundings was provided by the standard 5 oz army hand grenade with a 7 sec delay. These hand grenades are freely obtainable, easily prepared and reliable. Simple experiments suggested that the grenades exploded at a depth of about 5 fm, and this was confirmed later by observations of bubble pulses.

The impulses received at the transducer from the direct and echo wave-trains were pre-amplified at the head of the transducer and then transmitted to the observation room on the bridge. After passing through a 1000 cycle high-pass filter the resulting signal was amplified and the restricted output of the amplifier recorded (after suitable power amplification) on one trace of a four-trace spark recorder. Timing dots were provided at 1/40 sec intervals by a relaxation oscillator, and a chronometer recorded one-second intervals.

The choice of a high-pass frequency of 1000 c/s for the filter was fairly arbitrary. The selection of the optimum frequency would have entailed a good deal of analysis or experiment and since one of the objects of the experiment was the development of a flexible unit to be used with any transducer available it was considered pointless to achieve optimum matching of all contributary factors in this particular case. In practice a 500 c/s high pass filter was also tried but discarded as being much inferior in signal/noise ratio.

EXPLOSION SOUNDINGS

The equipment was initially tested from *Lachlan* in 1955 over the Tonga and Kermadec Trenches and 659 explosion soundings were made along lines shown in Fig. 5. For the major part of the voyage a heavy swell persisted and sounding ceased at the ends of lines G and I due to excessive motion of the ship. The grenades were dropped from the stern (quarterdeck) during calm condition and from the forecastle deck during heavy swells. Along lines A and B *Lachlan's* speed was 12·0 kt and thereafter 9·9 kt. No precautions were taken to reduce noise within the ship itself, all activities continuing normally. However any blow on the hull of the ship or on any part rigidly connected to the transducer housing produced noise on the record, and although the characteristics of such noise differ from the characteristics of the echo signal where the latter is of reasonable amplitude, nevertheless over the critical portions of the Tonga-Kermadec trench where the echo signal was

weak a complete cessation of activity on board ship would have been valuable. In addition much noise was created by insecurely fastened mechanical joints and stores in the vicinity of the asdic dome.

The travel time differences of the direct and echo-signals read off the records were converted to depths by means of the Admiralty tables (MATTHEWS, 1939). The positions of the soundings were determined by dead reckoning between morning and evening star fixes with noon latitude control from sun observations. FISHER (1954) has examined in detail the principal corrections required in the explosion-oscillograph method of sounding and the present soundings have been corrected after the manner of his analysis.

The quality and strength of the echo-signals depend on several factors. Expansion of the wavefront results in displacement amplitude being inversely proportional to the distance from the explosion; the topography and nature of the sea bottom affect not only the strength of the echo but also its character; and the efficiency of the detector depends greatly on the attitude of the ship. Fig. 8 shows a good sounding (546) 2840 fm, with bubble pulse arrivals visible on both direct and echo returns. Soundings 554 and 555 of line T (Fig. 8) demonstrate the variability in the strength of the echo; these two soundings were taken under identical conditions within 2 min of each other across a flat sea-bottom with a change in ship's position of about one-third of a mile.

Contribution No. 28 from the N.Z. Oceanographic Institute.

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‡*Geophysics Division, Dept. of Scientific and Industrial Research, Wellington, New Zealand.*

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Deep-Sea Research, 1958, Vol. 5, pp. 29 to 35. Pergamon Press Ltd., London

Transpacific distribution of floating pumice from Isla San Benedicto, Mexico

ADRIAN F. RICHARDS

Abstract—A probable transpacific drift of floating trachytic pumice originating from the 1952 erruption of Volcán Bárcena on Isla San Benedicto off the west coast of Mexico is reported. Pumice from San Benedicto was collected in the Islas Revillagigedo and on Hawaii, Johnston, Wake and the Marshall Islands. It may have reached the Palau Islands 12,000 km from Isla San Benedicto. Identification was based primarily on the index of refraction of glass and phenocrysts. A comparative study of pumices collected from widely different geographic localities in the north Pacific between 1951 and 1956 indicates that San Benedicto pumice is sufficiently distinctive, compared to pumices from other sources, to be identified with certainty. The following mean drift rates in the North Equatorial Current were determined : to Hawaii 22 cm/sec (264 days – 4800 km) ; to Johnston Island 33 cm/sec (225 days – 6100 km); to Wake Island and Ailinginae Atoll in the Marshall Islands 18 cm/sec (about 560 days – 8700 km). A comparison between the actual drift and a computed drift from surface current charts is made and discussed. An average figure of 22 cm/sec also has been calculated for the rate of a trans-Indian Ocean drift of pumice, in the South Equatorial Current, originating from the 1883 volcanic eruptions of Krakatoa.

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INTRODUCTION

ALTHOUGH exotic pumice is not uncommon on islands in the Pacific Ocean (SACHET 1955), a few attempts have been made to determine its origin (HEDLEY, 1905 ; LACROIX, 1939a, 1939b ; MACDONALD, 1954, p. 123) and apparently none to compute rate of drift over an extended distance.

Concurrent with the August 1, 1952, eruption of Volcán Bárcena (RICHARDS and DIETZ, 1956) on Isla San Benedicto off the west coast of Mexico an extensive " drift bottle experiment " began which furnished an ideal opportunity to determine not only the extent of drift but also the mean rate. Fortuitously San Benedicto is located in the general region where the North Equatorial Current begins (Fig. 1).

DISTRIBUTION

The first report of drifting pumice from Isla San Benedicto was made when the *Horizon* of the Scripps Institution of Oceanograph passed through a large area of drifting pumice on August 24, 1952. At stations located 55 and 104 nautical miles approximately north of Isla San Benedicto (A and B, Fig. 1) specimens of pumice (Fig. 2), wood, barnacles (*Lepas anatifera**), gastropods (*Litiopa melanostoma*†), and *Halobates* eggs and larvae* were dip-netted by Mr. GEORGE SHUMWAY.

On September 13 the S.S. *Hawaiian Citizen* passed through a 64-mile area of discoloured water about 320 miles west-southwest of San Benedicto (C, Fig. 1). M. G. MICHAELEDES, Second Officer, noted that the pumice was aligned in southwest-northeast streaks, and that as the ship proceeded west the streaks became more

*Identification by Dr. LEO BERNER of the Scripps Institution.
†Identification by Mr. ROBERT PARKER of the Scripps Institution.

numerous and appeared to stretch to the horizon (U.S. Navy Hydrographic Office, 1952). Some of the floating blocks were observed to be about 3 ft sq. A sample was collected and submitted to the U.S. Navy Hydrographic Office whence it was forwarded to the Scripps Institution.

In September the S.S. *Virginia Lykes* steamed through a field of pumice that was about 345 nautical miles long (D-E, Fig. 1) with the densest concentration about 230 miles south-west of San Benedicto (F, Fig. 1). In December a copy of the following report from the Second Officer to the Hydrographic Office was sent to the Scripps Institution :

" On the morning of Sept. 20, 1952, bound from Panama to Yokohama, in lat. 15° 30′ [N], long. 110° 30′ [W], at 10 a.m. local time and 1730 G.M.T., we began passing through numerous patches of what appeared to be lava or volcanic ash. It was of various sizes, some as large as a man's head, but mostly the size of rough gravel. It was light grey in colour. We passed through it all that day and at 8 p.m. local time of Sept. 20, 0330 G.M.T. of Sept. 21, in lat. 16° 00′, long. 113° 02′, it had increased to huge patches surrounding the ship. After this time it began to decrease until at 6 a.m. local time of Sept. 21 and 1330 G.M.T., in lat. 16° 34′, long. 115° 37′, it had decreased to only occasional very small patches. By 8 a.m. local time and 1530 G.M.T. of Sept. 21 in lat. 16° 40′, long. 116° 09′, it had disappeared and no more was seen."

Pumice originating from Isla San Benedicto was collected on Isla Socorro and Isla Clarión, in the Islas Revillagigedo, on the island of Hawaii, and on Johnston Island during 1953. Only a little pumice was deposited on Hawaii (C. K. WENTWORTH, personal communication). According to EMERY (1956, p. 1516), beginning in March 1953 several hundred pounds of well rounded pieces of pumice, up to 7·5 cm in diameter, landed on Johnston Island and the nearby Sand Island. The greatest quantity arrived in September and October and filled screens and pipes of the water evaporators on Johnston.

By mid-February 1954 San Benedicto pumice had reached Wake Island and the Marshall Islands. Mr. FRED LIBBY collected a specimen 19 cm in length (Fig. 3) from the east side of Wake Island in the middle of February. Mrs. INA MOORE (personal communication) reported that such large pieces were rare on Wake ; it was mostly walnut to potato size and sparsely scattered on the beach. A moderate amount of pumice was present on Ailinginae Atoll, Marshall Islands, on February 10 and similar material was seen on Bikini Atoll a few weeks before, (JOHN ISAACS, personal communication).

In 1956 Dr. F. R. FOSBERG sent the writer pumice from five atolls in the Marshall Islands. On the east beach of Rongelap Islet pumice pebbles lay on both the upper part of the beach and on the flat back of the top of the beach. Small, rounded, fine-grained pebbles were most common and in places covered the sand. Some of the larger pieces (San Benedicto pumice) were much fresher-looking than presumably older, non-San Benedicto material. Small corals were attached to certain specimens (F. R. FOSBERG, from field notes). San Benedicto pumice was not present in a number of samples examined by the writer which were collected in the Marshall Islands by FOSBERG in 1951 and 1952.

Attempts to identify San Benedicto pumice west of the Marshalls have been unsuccessful. Mr. A. B. BRONSON (personal communication) wrote that the drift apparently missed Guam. However, he reported the interesting observation that :

" During 1954 and early 55 a great amount of pumice washed up on the beaches in the Palau group of the Western Carolines. It was not unusual to pass through rather dense formations floating

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Fig. 3. Piece of San Benedicto pumice 19 cm long collected on the beach of Wake Island. Scale in centimetres. Scripps Institution of Oceanography photograph.

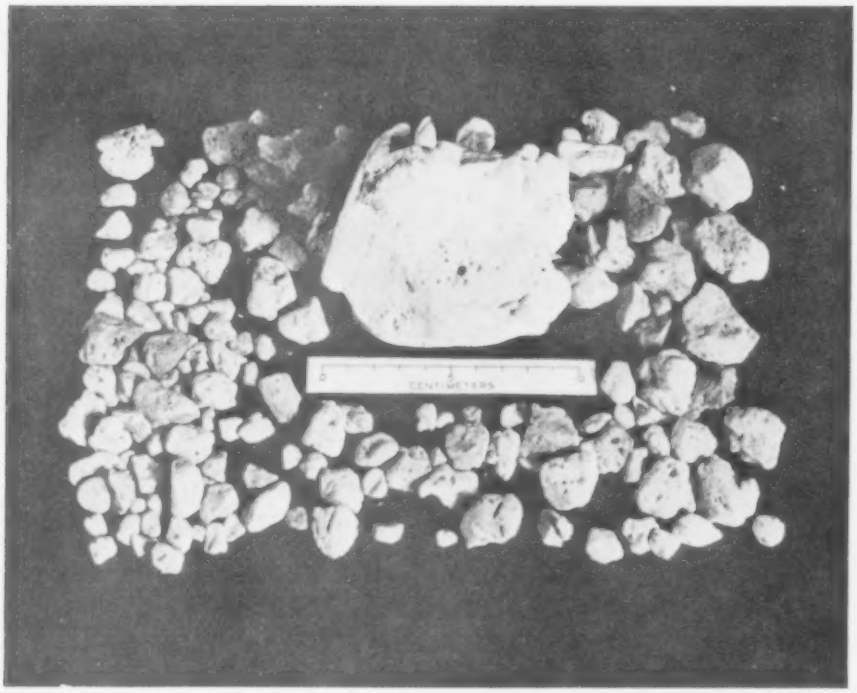

Fig. 2. Pumice collected floating in the Pacific Ocean about 104 miles north of Isla San Benedicto. A barnacle is attached to the top of the largest piece. U.S. Navy Official photograph.

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in the open sea near that group. All this material, or nearly all, bore a growth of barnacles and appeared to have been a long time at sea."

In February 1956 BRONSON noticed small blocks of pumice floating at sea between Palau and north-west New Guinea and wrote to the writer that :

"On the islands of Biak and Japen and in some of the adjacent atolls there were pieces of pumice washing back and forth on the beaches with the tide. There was not as much as there had been previously in Palau, but it still seemed to be drifting in that area."

Unfortunately no samples were collected.

IDENTIFICATION

The trachytic pumice from Isla San Benedicto was identified primarily by microscopical determination of the index of refraction of glass and indices of refraction of phenocrysts (Table 1). Colour and vesicular texture of the pumice were also used as an aid to identification. Phenocrysts were separated from the glassy matrix by hand picking and by ingestion of glass by hydrofluosilicic acid (see KNOPF, 1933). Index of refraction measurements were made using white light and liquids in 0·002 intervals for glass and feldspars and 0·01 intervals for pyroxene. The temperature correction of the high index liquids, composed of methylene iodide and sulphur, was not stated by the manufacturer ; 0·0007 — dn/dt was assumed in making adjustments for temperature. Orientation of mineral grains was determined from interference figures. Index of refraction measurements of the phenocrysts listed in Table 1 indicate a weight percentage of about Or_{55} $(Ab + An)_{45}$ for sanidine (TUTTLE, 1952, p. 559) and a molecular composition of about Ac_{30} Di_{70} for aegerine-augite (TROGER, 1952, p. 64), except from the Bárcena sample, which has a composition of about Ac_{20} Di_{80} ; the values of plagioclase weight percentage are obtained from CHAYES (1952, p. 51).

Phenocrysts of sanidine and aegerine-augite in the drifted pumice were comparatively abundant and plagioclase was rare. Plagioclase phenocrysts were not seen in samples from 320 miles west-southwest of San Benedicto, Socorro, Clarión, Hawaii, Johnston, Wake, and Ailinginae Atoll in the Marshall Islands. However, most of these samples were small ; had there been more material, plagioclase probably would have been found. The Rongelap Atoll sample was large and plagioclase was present.

A number of drift samples collected in the east, central, and west Pacific Ocean also were examined in order to determine and compare mineralogical variation. None of the samples from other sources resembles pumice from Isla San Benedicto, except for somewhat similar values obtained for the index of refraction of glass (1·491-1·510). Pumice from the 1952 eruption of Myojin Reef (NIINO, *et al.*, 1953 ; MORIMOTO and OSSAKA, 1955), which is located about 200 miles south of Tokyo, is particularly dissimilar. A sample examined by the writer contains quartz and the glass has an index of refraction of $1{\cdot}491 \pm 0{\cdot}003$.

ORIGIN OF PUMICE ON ISLA SAN BENEDICTO

There are only two possible sources on San Benedicto from which pumice could have been erupted : Volcán Bárcena and the eroded pyroclastic cone Montículo Cinerítico, which is located under and to the south of Bárcena. Bárcena is predominantly composed of volcanic dust or ash ; pumice from breadcrust bombs is not abundant and is darker, heavier, and poorly vesiculated compared to Montículo

Cinerítico pumice. Only pumice from Montículo Cinerítico resembles the drift pumice in appearance. The phenocrysts in pumice from both sources are nearly identical ; however, the index of refraction of glass differs slightly, ranging from 1·510 to approximately 1·523 in Bárcena pumice and comparatively constant at about

Table 1. *Determinative mineralogy of Isla San Benedicto pumice*

Location where collected	*Index of refraction of glass* (± 0·002)	*Index of refraction of sanidine* (± 0·002)	*Index of refraction of plagioclase* (± 0·002)	*Plagioclase composition*	*Index of refraction of aegerine-augite* (± 0·006)
Isla San Benedicto, Volcán Bárcena Pumice	1·516	N_x 1·522 N_y 1·527 N_z 1·528	N_x 1·530 N_y 1.534 N_z 1·538	An_{2-3}	N_x 1·713 N_y 1·724 N_z 1·743
Isla San Benedicto, Montículo Cinerítico pumice	1·503	1·521 1·527 1·528	1·532 1.536 1·541	An_{6-8}	1·726 1.734 1·761
Isla San Benedicto, drift pumice from Volteadura Beach	1·505	1·522 1·527 1·528	1·530 1·534 1·537	An_{2-3}	1·726 1·735 1·756
104 miles north of Isla San Benedicto 21° 02′N, 110° 34′W	1·502	1·521 1·527 1·528	1·535 1·540 1·546	An_{15-17}	1·727 1·734 1·762
320 miles west-southwest of Isla San Benedicto, 16° 54′N, 116° 20′W	1·504	1·521 1·527 1·528	see text		1·729 1·734 1·762
Hawaii Island, northwest coast	1·505	1·521 1·527 1·528	see text		1·727 1·738 1·755
Johnston Island	1·502	1·521 1·527 1·528	see text		1·725 1·737 1·756
Wake Island	1·502	1·521 1·527 1·528	see text		1·727 1·737 1·756
Marshall Islands, Ailinginae Atoll	1·505	1·521 1·527 1·528	see text		1·727 1·735 1·754
Marshall Islands, Rongelap Atoll	1.503	1.521 1·527 1·528	1·529 1·534 1·538	An_{2-3}	1·727 1·734 1·756

1·503 in Montículo Cinerítico pumice. It appears probable that little or none of the drift pumice originated from Volcán Bárcena ; apparently most if not all came from the part of Montículo Cinerítico blown up at the birth of Bárcena.

It is difficult to estimate how much pumice originated from Montículo Cinerítico. The magnitude of the craters of Bárcena and Montículo Cinerítico – the latter shown in photographs taken before the birth of Bárcena – indicates that about 3,000,000 m^3 of pumice and ash may have been blown up and deposited in the sea.

RATE OF DRIFT

Isla San Benedicto pumice – Distances, travel time in days, and calculated drift rates are tabulated in Table 2. Distances are based on straight-line travel from a Mercator projection. Travel time was computed on the assumption that pumice entered the water at San Benedicto on August 2, 1952, the second day of the eruption. Time of arrival at Hawaii, Johnston and Wake is believed to be correct within about one week. The mean drift rates are probably conservative.

If the large patches of floating pumice seen in the vicinity of the Palau Islands in late 1954 originated from Isla San Benedicto the computed drift rate would be about 18 cm/sec, based on a 12,000 km drift in approximately 790 days (to October 1, 1954). An earlier or later arrival of two months would only change this figure by about 10 per cent.

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Table 2. Drift rates of pumice from Isla San Benedicto

Location of drift pumice	*Collector*	*Date collected*	*Travel time in days*	*Distance from San Benedicto* naut. miles	km	*Travel per day* naut. miles	km	*Calculated drift rate* knots	cm/sec
104 miles north of Isla San Benedicto, 21° 02′N, 110° 34′W	G. SHUMWAY	24/8/52	22	104	193	4·7	8·7	0·2	10·1
320 miles west-southwest of Isla San Benedicto, 16° 54′N, 116° 20′W	M. G. MICHAELEDES	13/9/52	42	320	593	7·6	14·1	0·32	16·3
Hawaii Island, north-west coast	C. K. WENTWORTH‡	10/4/53	264	2600	4820	10·4	19·2	0·43	22·2
Johnston Island	K. O. EMERY	15/3/53	225	3300	6120	14·7	27·2	0·61	33·4
Wake Island	F. LIBBY	15/2/54	562	4700	8710	8·4	15·5	0·35	18·0
Marshall Islands, Ailinginae Atoll	J. Isaacs	10/2/54	556	4700	8710	8·5	15·7	0·35	18·2

‡Forwarded by G. A. MACDONALD.

All specimens of pumice collected from the sea or beaches that have been examined by the writer were rounded by abrasion (Figs. 2 and 3). Drift probably was induced predominantly by oceanic currents rather than wind, because floating San Benedicto pumice has little freeboard and the emergent part is streamlined.

Krakatoa pumice – A rate of drift similar to that of pumice from San Benedicto is obtained from calculations of the drift of floating pumice, presumably originating from the 1883 volcanic eruptions of Krakatoa in the Strait of Sunda between Sumatra and Java, across the Indian Ocean. Activity of Krakatoa that ejected pumice appears to have started about May 20, 1883, and culminated with the violent eruptions of

August 26-27 (JUDD, 1888). Charts published by MELDRUM (1885) show the drift of this pumice across the Indian Ocean as it was observed by ship captains. According to SCOTT (1888) the pumice reached the coast of Natal, south-east Africa, September 27-28, 1884. Assuming an eruption of the pumice in May, 1883, the rate of drift in the South Equatorial Current over a distance of about 8500 km would be approximately 20 cm/sec ; erupting in August, 1883, it would be about 24 cm/sec. An average of these two figures, or 22 cm/sec, appears to be a not improbable rate of drift. It is probably coincidental that this average is nearly identical to the 23 cm/sec average of four central Pacific drift rates of San Benedicto pumice in the North Equatorial Current.

In comparison with San Benedicto pumice it is noteworthy that JUDD (1888, p. 38) stated that Krakatoa pumice floated with a large portion of its mass above the water and he believed that the prevailing winds might have influenced the drift.

Computed drift – A comparison with the actual drift of San Benedicto pumice was made with the computed current drift from published surface current charts (U.S. Navy Hydrographic Office, 1947, 1950). Current roses, which show the frequency of direction and average current speed within the directions for quadrangles about five degrees square, were resolved for resultant vectors of the direction and speed of current drift. It was assumed that San Benedicto pumice travelled in the resultant direction of current drift, the distance depending on the resultant speed and the number of days during which the drift was applicable.

Using this method, beginning at Isla San Benedicto on August 1, 1952, a drifting object would not approach Hawaii until August 1953, when it would tend to gyral about 300 nautical miles north of Oahu (Fig. 1). Assuming a departure from lat. 16° N and long. 113° W on October 1, 1952, about the time when large quantities of pumice were observed in this area, a drifting object would travel approximately 360 miles south of Oahu by mid-August 1953 and would be 60 miles east of Johnston Island in early October, but over 500 miles east of Wake Island by the end of April 1954 (Fig. 1).

The drift track of this theoretical object would pass well north of the Marshall Islands and would arrive late at each of the islands on which San Benedicto pumice was collected. This is not too surprising considering the averaging processes used in the compilation of the charts and in making the computations given above. In conclusion, it is noteworthy that the range of current direction and velocity shown on the charts can easily account for the rate and direction of the actual pumice drift.

Radioactive tracer – WOOSTER and KETCHUM (in press) determined that the rate of drift of radioactive dissolved substances over a distance of about 7,000 km west of Bikini Atoll in the Marshall Islands was approximately 20 cm/sec. This figure approximates the 23 cm/sec average obtained from the rate of drifting San Benedicto pumice.

Acknowledgments—I am greatly indepted to all of the numerous people who donated samples of drift pumice and provided information on distribution. In particular, I am grateful to Dr. F. R. FOSBERG who made available field notes and his extensive collection of pumice from the Marshall Islands. At the Scripps Institution of Oceanography Prof. R. S. Arthur suggested the method of computing surface currents, and Profs. M. N. Bramlette and D. L. Inman kindly provided index of refraction liquids. I also wish to thank Dr. E. L. Hamilton of the U.S. Navy Electronics Laboratory who lent the petrographic microscope used in this study. Profs. K. O. EMERY, University of

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Southern California, R. S. ARTHUR, Scripps Institution and Dr. J. LYMANN of the U.S. Navy Hydrographic Office read the manuscript and offered helpful suggestions.

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On the wind driven ocean circulation

E. M. HASSAN

(*Received* 1 *July* 1957)

Abstract—A model of a wind driven ocean was considered to determine the vertical structure of the horizontal currents. The most restrictive assumptions were the absence of vertical motion and the constancy of the coefficient of exchange of momentum. The results of the model indicate a strong counter current under the intense western current. They also indicate that the current pattern in three dimensions is cellular.

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INTRODUCTION

THE ocean circulation is a fascinating and challenging problem that remains one of the outstanding unsolved problems in oceanography. Different models for the ocean have been worked out to emphasize different features (STOCKMANN, 1946 ; SVERDRUP, 1947 ; STOMMEL, 1948 ; MUNK, 1950 ; HIDAKA, 1950, 1951 ; NEUMANN, 1954, 1955). In these models the transport is considered as distinguished from the actual currents. Important as the transports are, they do not give a detailed picture of the vertical structure of these currents. HIDAKA (1955) therefore considered a model aiming to solve for the currents instead of the transports. In this model he assumed that the depth where the current vanishes is infinite, but because of computational difficulties he calculated the currents down to the depth of 225 m. Because it is felt that the difficulties resulted from a relatively complicated wind stress system it is proposed in this paper to treat a model similar to HIDAKA's with simpler wind stress. The depth will be taken as finite and the current pattern for any depth will be worked out.

THE MODEL

The proposed model is of a rectangular ocean of uniform depth, the sides lying in the east west, north south directions.

Equations and assumptions.

The equations of motion, and continuity used were

$$-f\rho v = -\frac{\delta p}{\delta x} + A\frac{\delta^2 u}{\delta z^2} \tag{1}$$

$$f\rho u = -\frac{\delta p}{\delta y} + A\frac{\delta^2 v}{\delta z^2} \tag{2}$$

$$\frac{\delta \rho u}{\delta x} + \frac{\delta \rho v}{\delta y} = 0$$

Where $f \equiv$ The Coriolis parameter

$u, v \equiv$ The velocities in the x and y direction respectively, x increasing to the east and y to the north.

$\rho \equiv$ The density

$A \equiv$ The coefficient of vertical exchange of momentum.

The equation of continuity was reduced utilising the expression for incompressibility to

$$\frac{\delta u}{\delta x} + \frac{\delta v}{\delta y} = 0. \tag{3}$$

The following assumptions are implied in the equations :

(1) Only the steady solutions are investigated.

(2) The inertia terms are neglected. This assumption can be justified if large scale phenomena are to be investigated (HIDAKA, 1950).

(3) The horizontal coefficient of exchange of momentum is considered to be zero. This can be justified away from the coasts (MUNK, 1950).

(4) The vertical coefficient of exchange of momentum is considered to be constant.

(5) The vertical component of velocity is considered to be equal to zero.

(6) The fluid is considered to be incompressible.

The boundary conditions on the model are :

(1) Vertical boundaries are streamlines.

(2) There is no motion at the bottom of the ocean.

(3) The wind stress at the surface has the components.

$$\tau_x = -A\left(\frac{\delta u}{\delta z}\right)_{z=0} \tag{4}$$

and

$$\tau_y = -A\left(\frac{\delta v}{\delta z}\right)_{z=0} \tag{5}$$

The solution. The method by which the solution is sought is as follows :

We express the horizontal velocity profile in the vertical direction as a Fourier series between 0 and $\pi/2$. In order that the lower boundary condition be satisfied automatically we choose the series to be composed only of odd cosines. This does not affect the generality of the solution in the range in which we are interested. We then solve for the Fourier coefficients. These completely define the profile.

Let u and v be expanded in Fourier series of the form

$$u = \sum_{s=1}^{\infty} u_s \cos \frac{(2s-1)\pi z}{2h}$$

$$v = \sum_{s=1}^{\infty} v_s \cos \frac{(2s-1)\pi z}{2h}$$

Where

$$u_s = \frac{2}{h}\int_0^h u \cos \frac{(2s-1)\pi\zeta}{2h}\, d\zeta \tag{6}$$

$$v_s = \frac{2}{h}\int_0^h v \cos\frac{(2s-1)\,\pi\zeta}{2h}\,d\zeta \tag{7}$$

and $h \equiv$ the depth of the ocean.
Also let $\delta^2 u/\delta z^2$ and $\delta^2 v/\delta z^2$ be expanded in Fourier series of the form

$$\frac{\delta^2 u}{\delta z^2} = \sum_{s=1}^{\infty} a_s \cos\frac{(2s-1)\,\pi z}{2h}$$

$$\frac{\delta^2 v}{\delta z^2} = \sum_{s=1}^{\infty} b_s \cos\frac{(2s-1)\,\pi z}{2h}$$

Where

$$a_s = \left\{\frac{2}{h}\frac{\tau_x}{A} - \frac{(2s-1)^2\,\pi^2}{4h^2}\,u_s\right\}$$

and

$$b_s = \left\{\frac{2}{h}\frac{\tau_y}{A} - \frac{(2s-1)^2\,\pi^2}{4h^2}\,v_s\right\}.$$

Thus

$$\frac{\delta^2 u}{\delta z^2} = \sum_{s=1}^{\infty}\left(\frac{2}{h}\frac{\tau_x}{A} - \frac{(2s-1)^2\,\pi^2\,u_s}{4h^2}\right)\cos\frac{(2s-1)\,\pi z}{2h} \tag{8}$$

$$\frac{\delta^2 v}{\delta z^2} = \sum_{s=1}^{\infty}\left(\frac{2}{h}\frac{\tau_y}{A} - \frac{(2s-1)^2\,\pi^2\,v_s}{4h^2}\right)\cos\frac{(2s-1)\,\pi z}{2h} \tag{9}$$

Differentiating (1) with respect to y and (2) with respect to x we get

$$-f\frac{\delta\rho v}{\delta y} - \rho v\frac{\delta f}{\delta y} = -\frac{\delta^2 p}{\delta x\,\delta y} + A\frac{\delta^3 u}{\delta z^2\,\delta y} \tag{10}$$

$$f\frac{\delta\rho u}{\delta x} = -\frac{\delta^2 p}{\delta x\,\delta y} + A\frac{\delta^3 v}{\delta z^2\,\delta x} \tag{11}$$

Subtracting (10) from (11) and substituting from (7), (8) and (9) we get

$$\rho\frac{\delta f}{\delta y}\sum_{s=1}^{\infty} v_s \cos\frac{(2s-1)\,\pi z}{2h} = \sum_{s=1}^{\infty}\left\{\frac{2}{h}\left(\frac{\delta\tau_y}{\delta x} - \frac{\delta\tau_x}{\delta y}\right) - \frac{(2s-1)^2\,\pi^2\,A}{4h^2}\left(\frac{\delta v_s}{\delta x} - \frac{\delta u_s}{\delta y}\right)\right\}$$
$$\left\{\cos\frac{(2s-1)\,\pi z}{2h}\right\}$$

This equation must hold for all values of z. In all its terms the dependency on z occurs only as $\cos n\,\pi\,z/2h$, n being an odd integer. Therefore the coefficient of $\cos n\pi z/2h$ must vanish for every n separately.
Thus

$$\rho\frac{\delta f}{\delta y}\,v_s = \frac{2}{h}\left(\frac{\delta\tau_y}{\delta x} - \frac{\delta\tau_x}{\delta y}\right) - \frac{(2s-1)^2\,\pi^2\,A}{4h^2}\left(\frac{\delta v_s}{\delta x} - \frac{\delta u_s}{\delta y}\right) \tag{12}$$

Substituting from (6) and (7) into the equation of continuity it becomes

$$\sum_{s=1}^{\infty}\left(\frac{\delta u_s}{\delta x} + \frac{\delta v_s}{\delta y}\right)\cos\frac{(2s-1)\,\pi z}{2h} = 0$$

By the same reasoning as before, equating the coefficient of $\cos n\pi z/2h$ to zero we obtain

$$\frac{\delta u_s}{\delta x} + \frac{\delta v_s}{\delta y} = 0. \tag{13}$$

Equation (13) enables us to introduce a system of stream functions ψ_s such that

$$u_s = \frac{\delta \psi_s}{\delta y}, \qquad v_s = -\frac{\delta \psi_s}{\delta x}.$$

Equation (12) thus becomes

$$\rho \frac{\delta f}{\delta y}\frac{\delta \psi_s}{\delta x} + \frac{2}{h}\left(\frac{\delta \tau_y}{\delta x} - \frac{\delta \tau_x}{\delta y}\right) + \frac{A(2s-1)^2\pi^2}{4h^2}\nabla^2\psi_s = 0$$

Solution. Assuming that

(1) $\tau_y = 0, \qquad \tau_x = \tau_0 \cos\dfrac{\pi y}{b}$

(2) $\dfrac{\delta f}{\delta y} = \beta =$ constant

(3) The corners of the ocean have the ordinates, 0, 0 ; λ, 0 ; λ, b ; 0, b.

The solution is then

$$\psi_s = \gamma_s\left(\frac{b}{\pi}\right)^2 \sin\frac{\pi y}{b}\left[p_s e^{A_s x} + q_s e^{B_s x} - 1\right]$$

Where

$$\gamma_s = -\frac{8\tau_0 h}{Ab\pi(2s-1)^2}$$

$$p_s = \frac{1 - e^{B_s\lambda}}{e^{A_s\lambda} - e^{B_s\lambda}}, \qquad q_s = 1 - p_s$$

$$A_s = -\frac{\alpha_s}{2} + \sqrt{\frac{\alpha_s^2}{4} + \frac{\pi^2}{b^2}}, \qquad B_s = -\frac{\alpha_s}{2} - \sqrt{\frac{\alpha_s^2}{4} + \frac{\pi^2}{b^2}}$$

and

$$\alpha_s = \frac{4\rho B b^2}{A(2s-1)^2\pi^2}.$$

If

$$\psi = \sum_{s=1}^{\infty}\psi_s \cos\frac{(2s-1)\pi z}{2h}$$

then

$$u = \frac{\delta\psi}{\delta y}, \qquad v = -\frac{\delta\psi}{\delta x}.$$

The solution was calculated for one particular case using the following values :

$h = 1500$ m $\qquad b = \pi \cdot 1000$ km $\qquad \lambda = 5000$ km

$\tau_0 = -2$ dynes cm^{-2} $\qquad A = 500$ g cm^{-1} sec^{-1} $\qquad \rho = 1{\cdot}03$ g cm^{-3}

and $\beta = 1{\cdot}5 \times 10^{-13}$ cm^{-1} sec^{-1}

The calculation was carried out for s 1, 2, - - - - -, 11, 12.

and

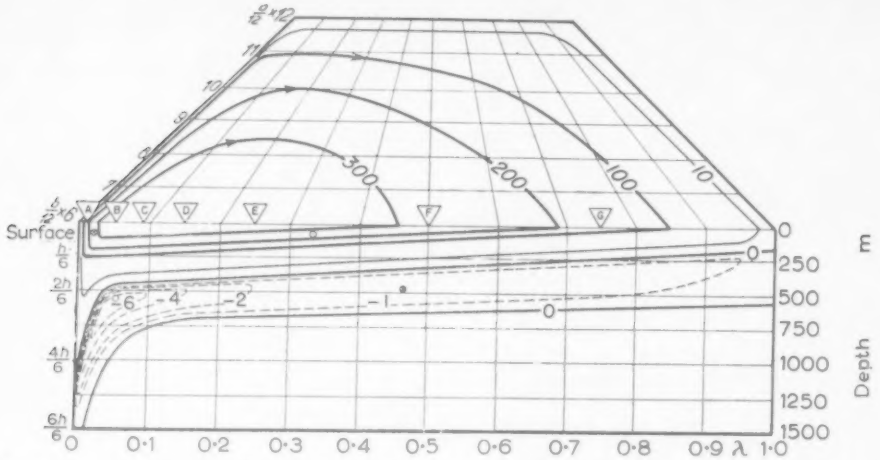

Fig. 1. The surface streamlines in the northern half of the ocean with a vertical section along the central parallel of latitude showing the convolution of the streamlines.

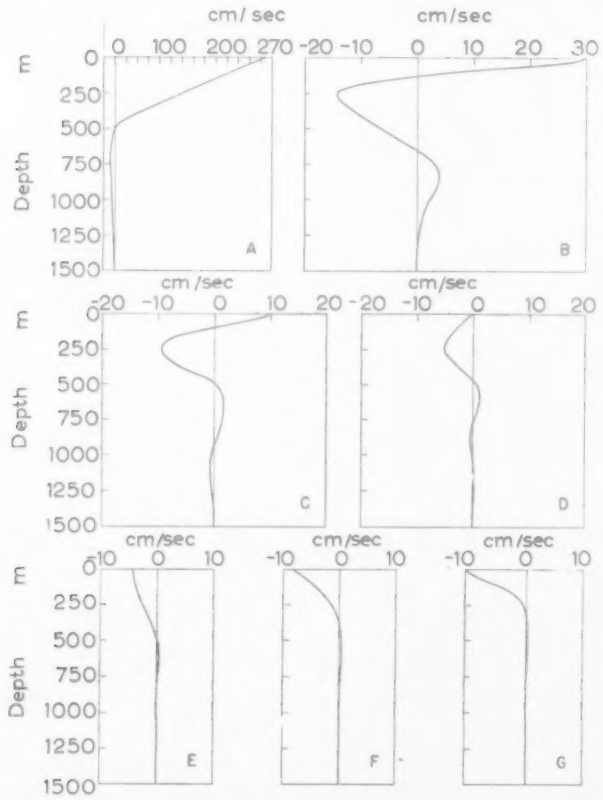

Fig. 2. The vertical profile of the horizontal velocity at selected points in the ocean, as indicated in Fig. 1.

$$\psi = \sum_{s=1}^{12} \psi_s \cos \frac{(2s-1)\,\pi z}{2h}$$

was calculated for the levels $z = 0,\ h/6,\ 2h/6,\ 3h/6,\ 4h/6,\ 5h/6$.

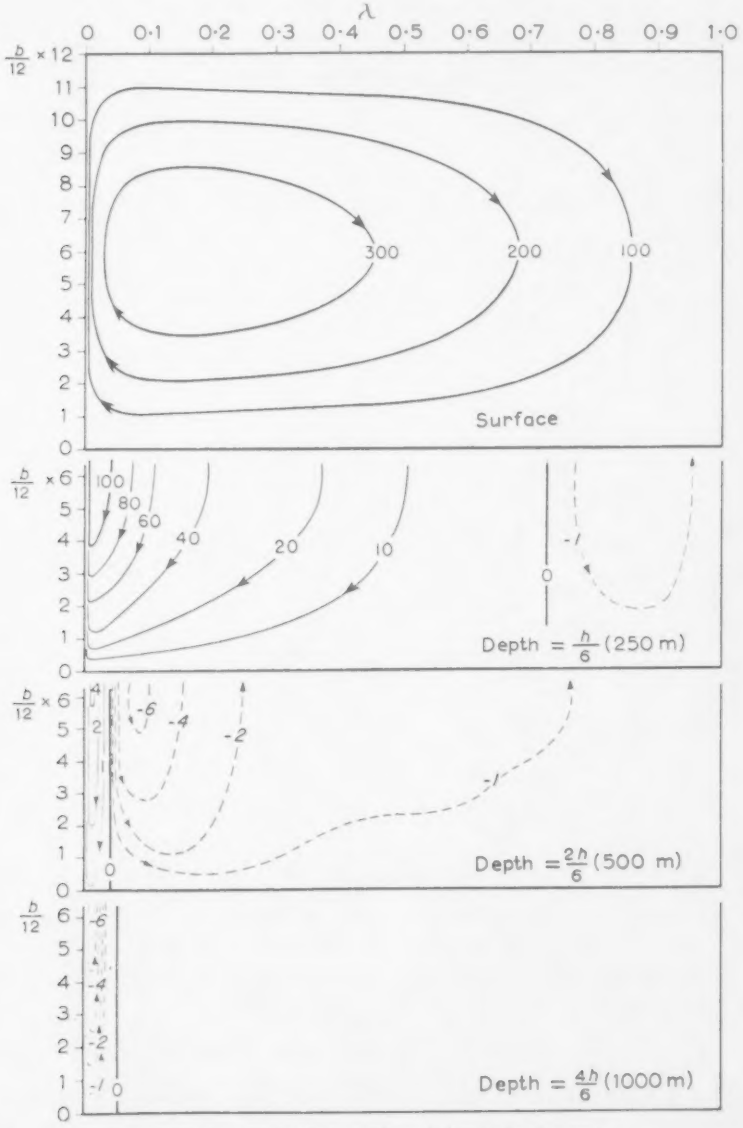

Fig. 3. The streamlines at selected depths in the ocean.

RESULTS

The main features of the solution are as follows :

(1) The strongest currents are meridional and appear on the western side of the ocean at the surface (Figs. 1 and 3).

(2) Beneath the intense northerly current on the western side of the ocean there is a southerly current, but the deep sea circulation is not the opposite of the surface circulation in the whole ocean.

(3) The surface current constitutes one gyre, but the current system in three dimensions consists of several cells.

(4) Not all of the current cells come to the surface.

(5) The cells shift their positions to the west at deeper levels and new cells appear from the east.

(6) The speed of the maximum current in each cell is less than that in cell immediately above it.

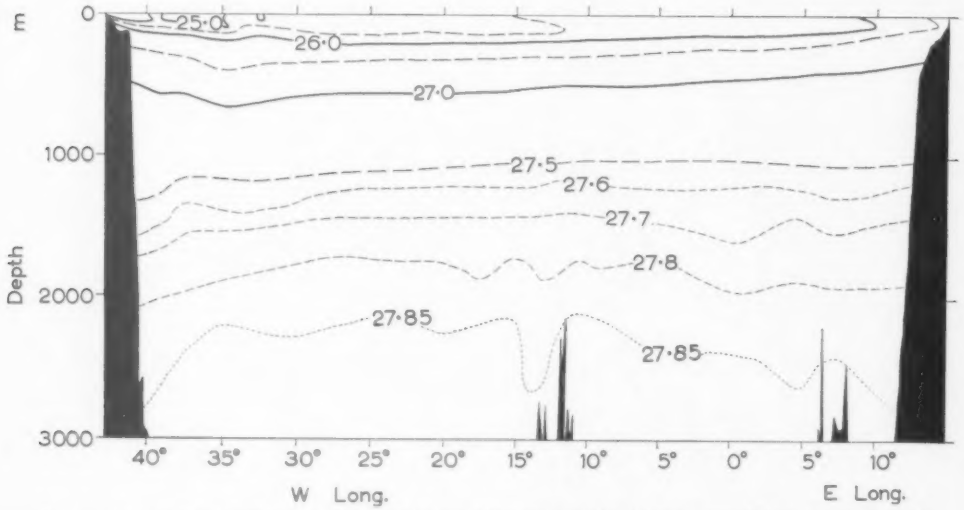

Fig. 4. The vertical section of the density as observed in the *Meteor* expedition approximately along the parallel of latitude of 22° south.

OBSERVATIONS

It is of interest to compare the results just obtained with observations. Realizing how simple the model is and how drastic some of the assumptions are, the degree of similarity between the results and the observations is surprising. These similarities can be summarized as follows :

(1) The westward intensification of the current is observed in every cell.

(2) Under the main north-going current on the western side of the ocean, there flows a southerly current. A southerly current has been recently observed under the Gulf Stream (SWALLOW and WORTHINGTON, 1957).

(3) If we add the assumption that, except for the boundaries, the convolution of streamlines in a current cell defines an *iso*pycnal surface, then a vertical section of *iso*pycnals along a parallel of latitude should look similar to the lower part of Fig. 1. Fig. 4 shows a vertical section of *iso*pycnals approximately along the parallel of

latitude of 22° south as observed in the *Meteor* expedition 1925-1927 (WUST and DEFANT, 1936) and the similarity is fair.

The constants used for the calculation of

	$\alpha_s = 10^4$ km^{-1} ×	$\gamma_s = 10^9$ cm^{-1} ×	$A_s = 10^3$ km^{-1} ×	$\beta_s = 10^3$ km^{-1} ×	p_s
ψ_1	2817·7	4863·4	3·549	− 281·78	·9824
ψ_2	313·08	540·38	31·91	− 31·340	·8525
ψ_3	112·70	194·54	88·04	− 11·349	·6439
ψ_4	57·505	99·253	168·94	− 5·9194	·4297
ψ_5	34·787	60·042	266·98	− 3·7457	·2632
ψ_6	23·287	40·194	370·48	− 2·6992	·1569
ψ_7	16·673	28·778	468·26	− 2·1356	·0962
ψ_8	12·523	21·615	553·70	− 1·8060	·0628
ψ_9	9·7500	16·828	625·00	− 1·6000	·0439
ψ_{10}	7·8054	13·472	683·19	− 1·4637	·0328
ψ_{11}	6·3894	11·028	730·32	− 1·3693	·0260
ψ_{12}	5·3265	9·1936	768·53	− 1·3012	·0214

Acknowledgments—This paper is part of a thesis submitted to New York University in partial fulfillment for the requirements for the degree of doctor of philosophy. The project was supported in part by the Office of Naval Research, Washington, D.C., under contract Nonr-285 (12) and in part by the Egyptian Government.

The writer wishes to express his thanks to Prof. G. NEUMANN for his inspiring guidance and valuable help throughout all phases of the work. He also wishes to thank Prof. W. J. PIERSON, Jr. for his interest and for his constructive criticisms and suggestions. To Prof. J. E. MILLER, Mr. H. STOMMEL and Dr. G. VERONIS, the writer is indebted for their critical reading of the manuscript, and to Mr. J. PANDOLPHO for his assistance in the computation of the results.

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Deep-Sea Research, 1958, Vol. 5, pp. 44 to 50. Pergamon Press Ltd., London

Observations on a scattering layer at the thermocline

D. E. WESTON

(*Received* 31 *October* 1957)

Abstract—A strong and extensive sound scattering layer has been observed in the North Sea, at the depth of the summer thermocline. The behaviour of the scatterers in daylight and at night is discussed. Calculations show that the echo is not directly due to the physical discontinuity, confirming the usual biological theory for its origin. There is a probable identification of traces due to both plankton animals and fish. The scattering layer also acts as a marker for the thermocline, making possible some continuous measurements of thermocline depth.

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INTRODUCTION

THERE have been many accounts of deep scattering layers detected by echo-sounding, but rather fewer reports of shallow layers or layers connected with density changes. In 1950 SCHÜLER and KREFFT (1951) observed a scattering layer in the North Sea, which they thought to be associated with a thermocline, and TUCKER (1951) reported a like case. TROUT *et al.* (1952) have demonstrated the correspondence between some complicated bathythermograph records and scattering layer measurements, and HERDMAN (1953) has found a similar relation. CUSHING *et al.* (1955 and 1956) have recently reported some further echo layers at thermoclines. The results of SCHÜLER and KREFFT are of particular interest here, since some of them were taken close to the area of the present work. Their 30 kc/s echograms in this area are very similar to those reported here.

The present observations were made possible only because R.R.S. *Discovery II* was on the Great Fisher Bank in the central North Sea doing other work, which meant however that not much effort was available for investigating the scattering layer. This particular layer is worth describing because of its extraordinary strength, persistence and extent.

THE OBSERVATIONS

The layer was observed between August 8th and 14th, 1954, extending at least 110 miles north from 56° 05′N, 03° 15′E. The true extent of the layer was not found. There was usually a strong reflection from the region of the thermocline, and sometimes from patches above and below it. A Kelvin-Hughes type 26E teledeltos echo-sounder was used at full gain, with the " standard " 10 kc/s magnetostriction transducers on *Discovery* (see HERDMAN, 1955). Some examples in Fig. 1 show the variation of appearance with ship speed. There are 4-minute timing marks near the top, and typical traces of fish near the bottom in Fig. 1 (a). The first 10 fm or so are partially obscured by reverberation within the ship's structure, which is indeed present over the whole depth range. This reverberation was much worse for the " stabilized " 10 kc/s transducers, which are suspended in a water-filled tank at the bottom of the ship, rendering them useless for scattering layer observations. No trace of the layer was found using a 30 kc/s set in August (which is not necessarily

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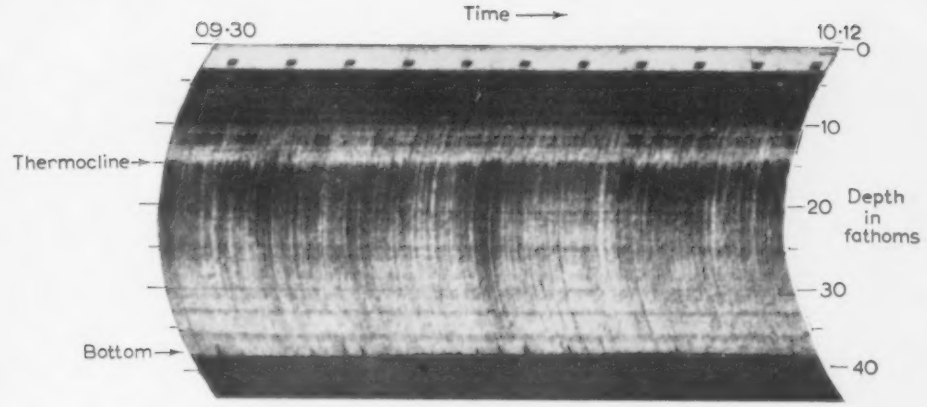
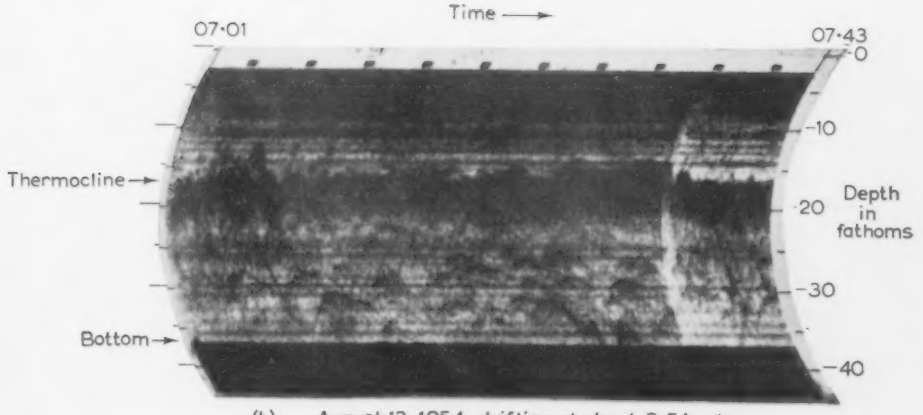


(a) August 9. 1954 underway at about 7 knots
56°26′-21′N, 03°15′E
(a)



(b) August 13. 1954 drifting at about 0·5 knots
near 56°05′N, 03°15′E
(b)

Fig. 1. Examples of the scattering layer.

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significant), nor with either set in October. The strength of the layer return varied considerably along the ship's track, and on one occasion it disappeared altogether for a few minutes.

The line along which observations were made lies right in the centre of the North Sea, and the water depth is nearly constant at about 37 fm. In August there is an exceptionally sharp and strong thermocline present over a wide area ; which is interesting because of the perfection of the temperature step form. Fig. 2 shows a tracing of a typical bathythermogram. From the measurements made at the time the mean temperatures above and below the thermocline may be taken as 58°F and 44·2°F (13·8°F difference), with a thermocline about 2 fm thick at a mean depth of 15 fm. The salinity is a little greater below the thermocline. In October the thermocline is both weaker (5·4°F difference) and deeper (25 fm). The temperature and salinity structure in the North Sea has been described by DIETRICH (1951) and the formation of the thermocline in this area has been discussed by DIETRICH and by LUMBY (1955). Some further measurements of water structure by DIETRICH and some turbidity measurements by JOSEPH were made near the present site in August, 1953, (see BÖHNECKE, 1955). The turbidity-depth curves show a sharp maximum at the thermocline, and quantities of plankton and detritus were found there.

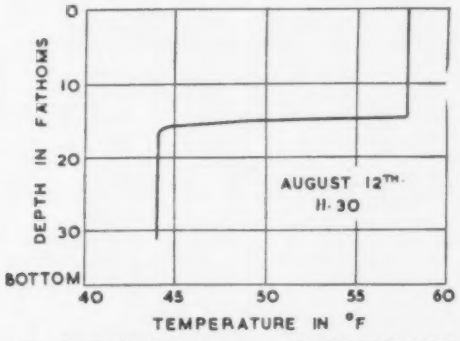

Fig. 2. Bathythermogram at 56° 05′N, 03° 15′E.

EXAMINATION OF THE SCATTERING TRACES

Comparisons show that the echo layer depths always lie within the region of thermocline gradient found on the bathythermograms, and that these two depth measures rise and fall together. Some of the comparisons are shown in Fig. 3, and indicate that the accuracy is insufficient to determine from which part of the thermocline the echo returns. Fig. 3 also shows that there is no apparent diurnal variation of layer depth (correlation of depth with other factors is discussed later). However, measurements made on August 8th 110 miles to the north, where the thermocline had become very broad, showed after sunset a layer steadily rising within the thermocline. Fig. 3 also shows that whereas there were usually some scatterers recorded below the thermocline during the daytime, they were never found there at night. The effect of light on fish, and the diurnal migration of the *deep* scattering layer following the light intensity, have been known for several years.

The records made with *Discovery* drifting, such as Fig. 1 (b), show up structure in the field of scatterers. The comet-like traces are produced by scatterers or groups

of scatterers (probably fish) which are small compared to the cross-section of the echo-sounder beam (see e.g. CUSHING and RICHARDSON, 1955). Thus the comet heads are formed at the closest approach of the scatterer to the echo-sounder transducer, and the tails correspond to the angular limits of the beam. The comet curves are essentially hyperbolae, modified slightly by the curved depth scale and the separation of the

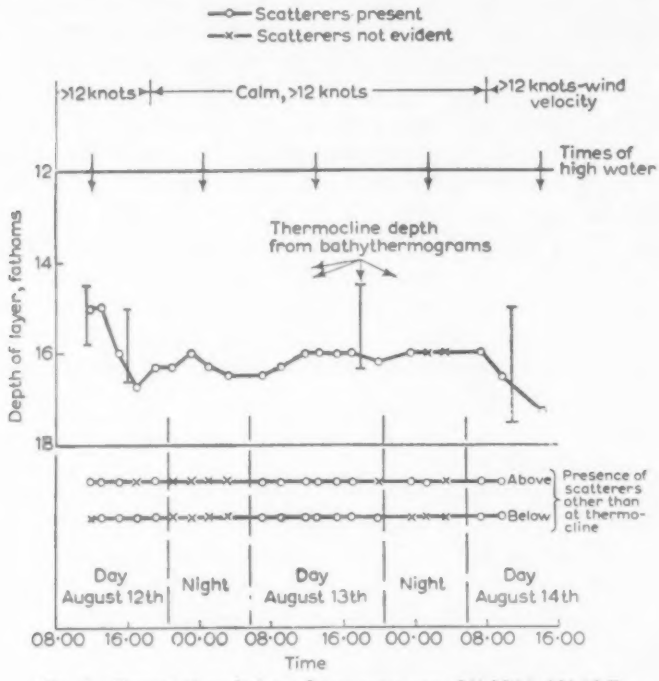

Fig. 3. Temporal variation of scatterers near 56° 05′N, 03° 15′E.

transmitting and receiving transducers. The ratio of the apparent depths of head and tails gives the cosine of the semi-angle of the beam (provided the echo-sounder passes nearly overhead). Taking the mean of several comet observations the beam intensity is found to fall off appreciably at 25°, and to produce no trace beyond 42°. This may be compared with the theoretical figure of 9 dB down at the maximum of the secondary lobe, occurring at 27° for a uniformly illuminated 22 in. radiator at 10 kc/s. Now the width of the comet is proportional to the relative velocity of ship and scatterer ; and it is convenient to remember that the separation of the tails *at* 1·12 times the apparent depth of the head corresponds to a movement *equal* to the apparent depth of the head (and a semi-angle 26·6°). From examination of Fig. 1 (b), the velocity may be seen to be decreasing on that occasion, with a mean value of 0·5 knots. If the scatterers are supposed stationary in the water, this velocity may be identified with the rate of drift of the ship through the water. In Fig. 1 (a), the greater velocity alters the appearance considerably, and the narrowness of the comets makes it difficult to distinguish their twin tails. Examination of the scattering groups shows that they must occupy a volume *less* than about 2 m × 2 m ; and that their density is variable, but typically about one per 40 m × 40 m.

In addition to the groups there appears to be a diffuse background reflection at the layer, which is sometimes visible *above* the layer at night. This behaviour may be explained if there are planktonic creatures present, which are driven down by the light intensity during the daylight. They would be held at the layer by the fractional density increase of 0.0017. Some vertical net hauls were taken through the thermocline in both August and October, producing catches of zooplankton consisting mainly of copepods, sagittae and medusae. In August the sagittae or arrow-worms were almost entirely *S. elegans* with but a few *S. setosa*, whereas in October most of the adult sagittae were *S. setosa*. The significance of this lies in the use of sagittae as indicator animals (RUSSELL, 1935, 1939). The *S. elegans* which predominated in August are typical of the nutrient-rich waters, partly oceanic in origin, which might be expected to carry much marine life and produce a strong scattering layer; *S. setosa* being typical of poorer waters. No great effort was put into this sampling, and the chief scatterers may well have escaped.

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THE REFLECTION COEFFICIENT

Before drawing final conclusions on the cause of the scattering it is worth-while comparing the experimental reflection coefficient with that expected on various theories. Since there was no time to calibrate the echo-sounding system there are no measurements of this coefficient, but it is possible to estimate orders of magnitude from comparisons with sea-bottom echoes. In this way a typical thermocline reflection coefficient has been chosen as $-$ 50 dB, with $-$ 65 dB as the least detectable coefficient for a reflector at 15 fm.

Consider first the expected reflection from the thermocline alone, considered as a physical discontinuity. Going downwards through the layer the fractional decrease in sound velocity is 0·0178 and the fractional increase in density 0·0017. This produces a fractional decrease $\Delta = 0{\cdot}0161$ in the characteristic impedance Z. At very low frequencies the plane-wave amplitude reflection coefficient will be

$$R = -\Delta/2 = 0{\cdot}008 \quad \text{or} \quad -42 \text{ dB} \tag{1}$$

Now the thermocline is not in reality a perfect step, and in calculating the reflection coefficient the *shape* of the thermocline must be taken into account. Consider for example the impedance step replaced by a linear variation of impedance within the thermocline width L. The sound is normally incident (y-direction) with a phase constant k that is *practically the same* above and below the thermocline. Taking the y-origin in the middle of the thermocline

$$\begin{aligned} R &= \int_{-\infty}^{+\infty} \frac{dz}{2z} \exp(2jky) \\ &= \int_{-L/2}^{+L/2} -\frac{\Delta}{2L} \exp(2jky)\, dy \\ &= -\frac{\Delta}{2} \cdot \frac{\sin kL}{kL} \end{aligned} \tag{2}$$

The average reflection coefficient at high frequencies is thus the value from equation (1) divided by $\sqrt{2}\,kL$. For a 2 fm thermocline at 10 kc/s the reduction is 47 dB, giving $R = -89$ dB.

The thermocline may be further smoothed by fitting to it two exponential terms, such that :—

$$Z = Z_0 + \frac{\Delta Z}{2}\left\{1 - \exp\left(\frac{2y}{L}\right)\right\}, \qquad y < 0$$

$$= Z_0 - \frac{\Delta Z}{2}\left\{1 - \exp\left(-\frac{2y}{L}\right)\right\}, \qquad y > 0 \tag{3}$$

Integrating as in equation (2)

$$R = -\frac{\Delta}{2} \cdot \frac{1}{k^2 L^2 + 1} \tag{4}$$

Thus at high frequencies the reflection coefficient has the value from equation (1) divided by $k^2 L^2$. In the example the reduction is 88 dB, giving $R = -130$ dB.

The analyses above are the same as those for the Fourier analysis of a pulse, where the pulse amplitude corresponds to the first spatial derivative of the impedance. In general at sufficiently high frequencies the average reflection coefficient falls off as (frequency)$^{-n}$, where the n^{th} derivative of impedance is the first to have a discontinuity. The true reflection coefficient at the thermocline due to the physical discontinuity probably lies between those given by equations (2) and (4), say $R = -100$ dB. This is so much less than the practical value that the direct reflection from the discontinuity may be ignored. This conclusion need not apply to other examples, where the thermocline may be sharper or the frequency lower.

It is also possible to estimate the reflection from marine animals containing air bladders, if they are treated merely as a collection of very small bubbles. It is found that about $\frac{1}{4}$ ml of gas per square metre will have a reflection coefficient of -50 dB at 10 kc/s, provided it is evenly concentrated within a layer less than one sixth of a wavelength thick (about one inch). In practice the layer will be thicker and more gas will be needed, but the quantities still seem reasonable. The reflection would be enhanced by the presence of resonant bubbles, which have a diameter of 1·25 mm at 15 fm. Bladders of this size could well occur in fish larvae which are still planktonic.

THE IDENTIFICATION OF THE SCATTERERS

There is little doubt that the scattering layer is biological in origin, but it is worth summarizing the present evidence for the various possibilities.

(a) *The physical discontinuity.* The variations of reflection coefficient along the track show that the discontinuity is not directly the present cause of the reflection. This is supported by the calculations above.

(b) *Detritus.* When the layer echo vanishes at night there is sometimes a diffuse reflection from above the layer, which could not be due to suspended particles or detritus. Detritus held at the layer is therefore not the only cause of the background reflection, and probably does not contribute at all.

(c) *Plankton.* This is the only possibility left for the cause of the background reflection. It is probably due to plankton animals, possibly fish larvae with small air bladders.

(d) *Fish.* The traces near the bottom in Fig. 1 (a) and the comet traces in Fig. 1 (b) must be due to fish. The comet scatterers are quite mobile, and are seen at, above,

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and below the layer. These are fish (such as herring) which concentrate at the layer depth, presumably to feed on the plankton.

THE THERMOCLINE

The presence of the scattering layer provides a very convenient method of observing the thermocline, particularly its depth variations. The use of this technique could well be extended, and by working at low frequencies it might even be feasible when there are no biological markers.

First it may be seen from close examination of the records (such as Fig. 1 (a)) that the " shorter wavelength " (less than 100 yd) variations in depth of the thermocline are generally less than 1 fm peak to peak. This upper limit is itself probably due to the method of estimation, since individual scatterers may vary in depth even with a flat thermocline. Fig. 4 shows evidence for a 2-mile wavelength with amplitude just over half a fathom, and for a wavelength of several miles with amplitude about 2 fm.

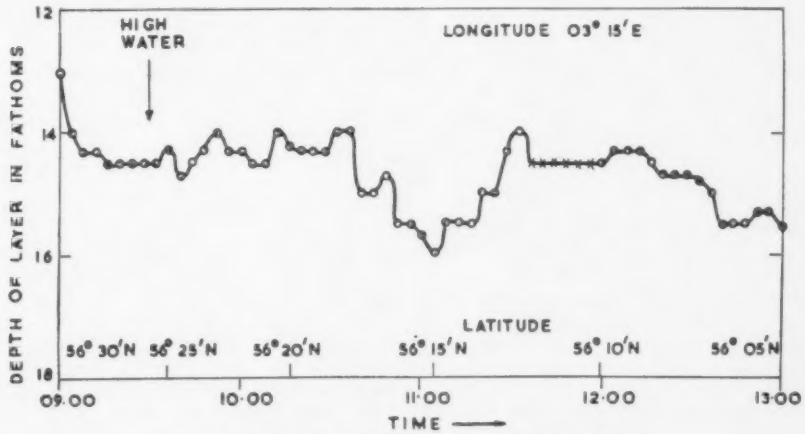

Fig. 4. Spatial variation of layer depth, August 9th.

Secondly the temporal variation may be seen in Fig. 3, with strong evidence for the 12½ hr tidal cycle with about ½ fm amplitude. Rather surprisingly the shallower thermocline depths occur at high water, suggesting that there is some opposing, indirect tidal effect. One such effect is the bodily movement of the water by the tidal currents. These are very slow, however and trace out a rough circle little more than a mile across. One may also speculate about internal waves in the thermocline surface generated by the tides (possibly at the shallow Dogger Bank lying just to the south). The theoretical velocity for such long waves is (following from expressions given e.g. by LAMB, 1906) :—

$$v = \sqrt{(gH\,\delta)} = 1{\cdot}02 \text{ knot} \tag{5}$$

where

$$\frac{1}{H} = \frac{1}{H_1} + \frac{1}{H_2} = \frac{1}{9 \text{ fm}} \tag{6}$$

Here δ is the density change at the thermocline, and H_1 and H_2 are the distances from thermocline to surface and bottom. The velocity expression should in general

be corrected for the Coriolis forces due to the earth's rotation, but these produce zero effect for propagation along a line of longitude. The predicted wavelength of about 12½ miles fits the spatial variation curve of Fig. 4 quite reasonably.

Thirdly note that on 13 August it was very calm, but on 12 and 14 August there was a moderate to fresh westerly breeze. Fig. 3 shows that the resulting turbulence led on both occasions to an increase in the thermocline depth. This increase is believed to be irreversible, and to show the mechanism by which the thermocline deepens throughout the summer.

Acknowledgments—The author is grateful to the Captain and Ship's Company of R.R.S. *Discovery II* for their helpful co-operation, and to the Admiralty for permission to publish this paper.

Royal Naval Scientific Service,
Admiralty Research Laboratory,
Teddington, Middlesex.

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Deep-Sea Research, 1958, Vol. 5, pp. 51 to 61. Pergamon Press Ltd., London

Selective transmission of light in tropical Pacific waters

WAYNE V. BURT

(*Received* 4 *September*, 1956)

Abstract—Transmission of light was measured at thirteen wave lengths on forty-six water samples drawn from the ocean in the eastern tropical part of the Pacific Ocean. Samples were taken at fifteen stations at depths ranging from the surface down to 1170 m. Transmission increased with wave length in a characteristic manner. Application of the Mie Theory of light scattering to the data indicated a decrease in the size of suspended particles with depth and with the clarity of the samples. A comparison with other oceanographic light-transmission data is made.

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THIS work was undertaken as a continuation of a study of the spectral transmission of natural waters (BURT, 1955a ; 1955b). A quartz prism spectrophotometer was used aboard ship in the deep ocean for the first time to furnish data which could be used to draw a light transmission curve for freshly drawn water samples which covered the whole visible spectrum. Such data is desirable in the study of the penetration of light into the sea as well as in optical determination of particle size of suspended material.

The data presented here were made by collecting water samples at different depths and measuring the spectral extinction with a spectrophotometer aboard ship. Measurements were made on both filtered and unfiltered samples. The principal problem with this method was first pointed out by CLARKE and JAMES (1939), who showed that when samples were stored before analysis, it " – – increased the absorption per metre as measured in the laboratory from two to four times greater than the absorption based on field measurements." Presumably, this increase in the turbidity in the stored samples is related to biochemical reaction within the stored samples. All of the measurements reported on in this paper were made within 1 hr of the time the samples was brought aboard.

METHOD AND RESULTS

Surface samples were drawn in a plastic bucket over the bow of a slowly moving ship to prevent contamination from the ship. These samples were then immediately transferred to thoroughly flushed bottles for transfer to the ship's laboratory. Subsurface samples were collected by Nansen bottles. The insides of the bottles were coated with an epoxy resin to prevent contamination.

Measurements were made with a Beckman Model DU Quartz Prism Spectro photometer. The spectrophotometer was equipped with a special factory-supplied long cell (50 cm) assembly (BECKMAN, 1950 ; BURT, 1952), which had been modified for work at sea. The modifications consisted of : a dry nitrogen, or dry air spray, on the first surface mirrors and the end of the glass cell to prevent corrosion and condensation ; stronger hinges, and a 5 lb weight on the lid of the cell assembly ; and a thick, soft, rubber-light gasket between the lid and the cell assembly.

Portions of some of the samples were filtered using a hydrosol HA Millipore filter with a nominal pore size of 0·5 μ (GOLDBERG, BAKER and FOX, 1952).

The instrument readings were converted to per cent transmission per metre T (λ), and extinction per metre κ (λ) ($T = e^{\kappa}$) where both T and κ refer to the effects of suspended and dissolved material in the water and do not take into account the effects of the water medium itself. This is because the instrument is a comparator type, requiring a pure water blank or standard to compare each natural sample with. Both double glass distilled, double filtered, and double filtered deep water (3000 m) were used as standards. The two standards are similar optically (CLARKE and James, 1939). Small errors are introduced into the readings by small, unknown amounts of suspended and coloured dissolved materials, which are always present in the standards.

Locations where samples were drawn are shown on Fig. 1. These samples were taken during the last half of the Scripps Institution of Oceanography East-Tropic Expedition in November and December, 1955. The exact location of stations, along with physical and chemical data for East-Tropic are presented in Scripps Institution of Oceanography, 1956.

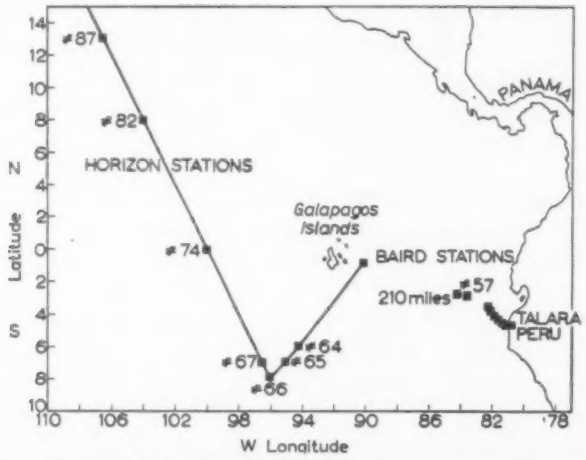


Fig. 1. Locations of stations where light transmission measurements were made.

Readings were made at thirteen wave lengths, ranging from 400 mμ to 800 mμ. These data were plotted, and a smooth curve drawn through the plotted points for each sample in order to smooth out the irregularities caused by the fluctuation of the instrument (BURT, 1955b). Repeated readings on the same sample indicate that the fluctuations are random. The smoothed percentage transmission curves are shown on Figs. 2 to 7. The raw data are plotted for some of the samples in order to show the degree of fluctuation of the instrument. The fluctuation becomes of increasing relative importance as the samples become clearer.

The difference in transmission between areas is in general agreement with the known biological activity of the region. In the seven surface samples taken in the Peru Current, there is a general increase in transmission as one leaves the shore. Of the five areas sampled (Peru Current, south west of the Galapagos Islands, on the equator, in the counter current, and in the north Equatorial Current), the lowest

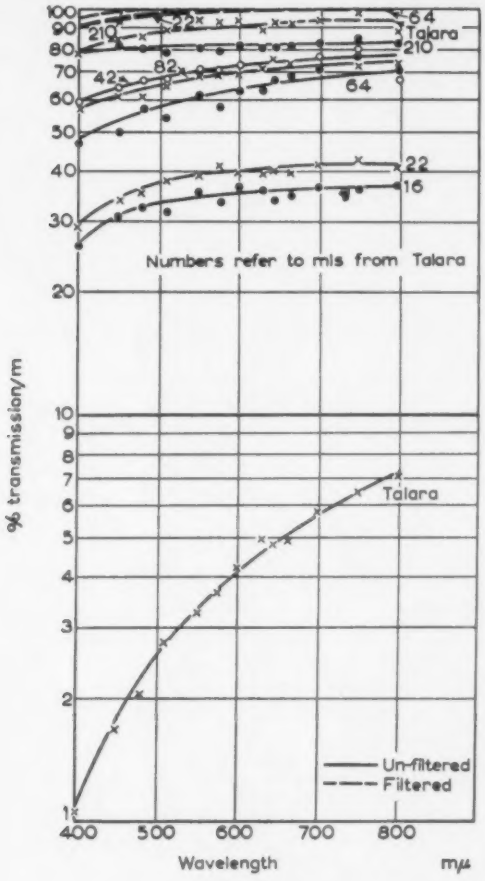
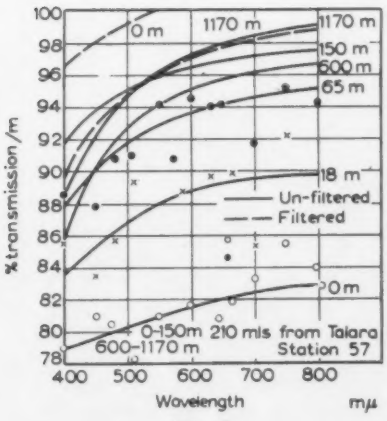


Fig. 2.



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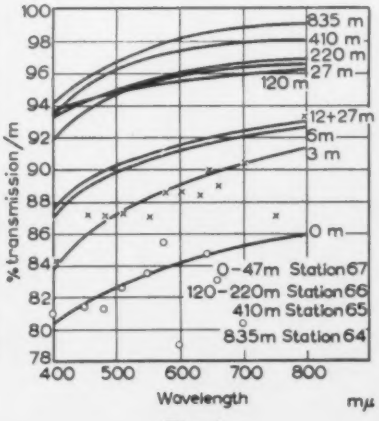
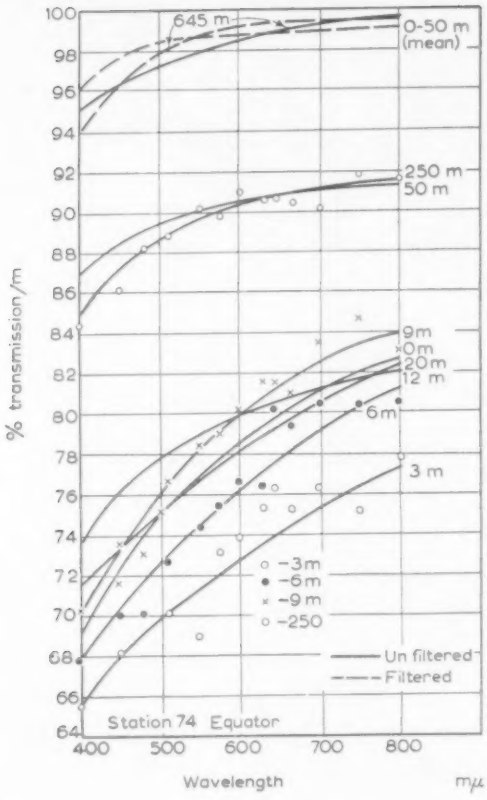


Fig. 4.

Figs. 2–4. Light transmission as a function of wave length. Values are for the combined effects of suspended and dissolved materials only. They do not take into account the extinction of the water itself, due to the fact that optically pure water was used as a standard of comparison.



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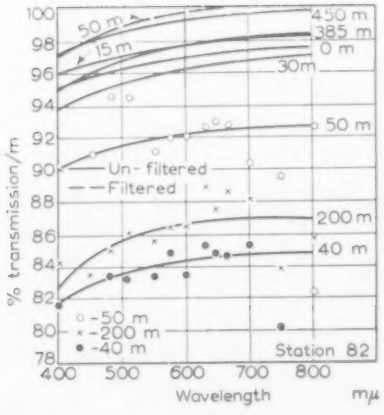

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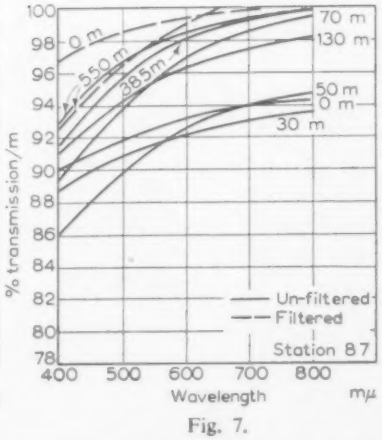

Fig. 7.

Figs. 5–7. Light transmission as a function of wave length. Values are for the combined effects of suspended and dissolved materials only. They do not take into account the extinction of the water itself, due to the fact that optically pure water was used as a standard of comparison.

transmission was in the Peru Current ; the next lowest was at the equator. The upwelled water along the coast of Peru creates one of the richest biological areas in the world, and the greatest biological activity is found near shore (GUNTHER, 1936). Upwelling along the equator also creates a rich biological region (CROMWELL, 1953).

The raw data did not show an absorption peak at 655 mμ which was recognizable for any of the samples. Readings had been made at 630, 645, 665 and 700 mμ for this purpose. The absence of this chlorophyll A absorption peak indicates the samples contained a smaller proportion of chlorophyll A pigmented material than had been previously found in Chesapeake Bay waters (BURT, 1955b).

Transmission curves for several filtered samples are shown on Figs. 2, 3, 5, 6 and 7. In some cases, the filter appeared to leave less optically effective material in the surface samples than in the deeper samples, Figs. 3 and 7 suggesting the possibility of a decrease in average suspended particle size with depth.

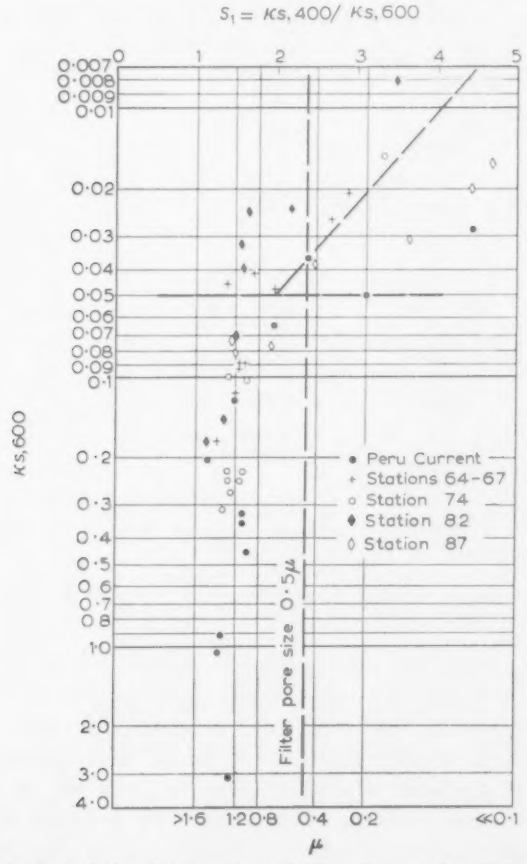

Fig. 8. Relation between the ratio S_1 and $\kappa_{s,600}$ for all data.

ESTIMATION OF PARTICLE SIZE FROM EXTINCTION CURVES

BURT (1955a ; 1955b) has shown, by using the Mie Theory of light scattering by particles, that the ratio, S_1, of the partial extinction coefficient at 400 mμ to the

partial extinction coefficient at 600 mμ may be used as a rough index of the particle size of suspended material in natural waters. If this ratio has a numerical value of one, all of the particles are large, compared to the wave length of light. As the ratio increases in value numerically, the average size of the light-scattering particles decreases. The ratio has a maximum value of approximately five for a distribution of particles with diameters so small compared to the wave length of light that Rayleigh scattering applies over the whole range of particle sizes present.

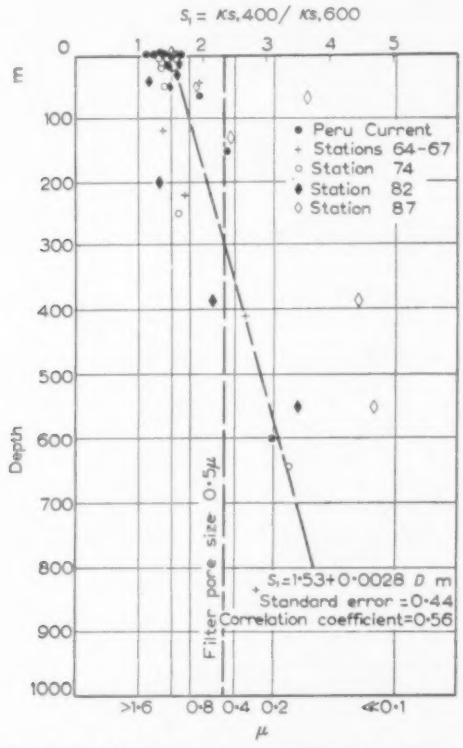

Fig. 9. Relation between S_1 and depth for all data.

Strict application of the Mie Theory requires knowing : (a) the frequency distribution of the particle sizes, (b) the refractive index of the particles and (c) the absorption properties of the particles. BURT, (1956) has given a graphical presentation of scattering efficiencies as a function of particle size, refractive index, and wave length. In this discussion, it has been assumed that the particles are uniformly sized, spherical, relatively non-absorbing, and have a relative refractive index of 1·15. For the semi-quantitative conclusion drawn, each of these assumptions may introduce some error. Addition of dissolved organic material, " yellow substance," (JERLOV, 1955) tends to increase the numerical value of the ratio due to high absorption at the blue end of the spectrum. The resolution of the instrument is not great enough to aid in estimating the relative importance of Rayleigh scattering from very fine material and the absorption from dissolved organic material. For this reason, the

particle sizes in this discussion are under-estimated by an unknown factor, probably not exceeding one-half.

The ratio, S_1, was computed for all of the data for the unfiltered samples. S_1 is plotted against the absolute value of $\kappa_{s,600}$ in Fig. 8, and against depth in Fig. 9. A size scale between S_1 and diameter, based on the aforementioned assumptions, is also shown on the bottom of the two figures. Using this size scale, the nominal pore size, 0·5 μ, on the millipore filter is drawn as a vertical line on each figure.

S_1 is nearly constant with $\kappa_{s,600}$ for the more turbid samples across the range of $\kappa_{s,600}$ from 3·2 to 0·05 (Fig. 8). In this range, the average value of S_1 is 1·47. For the clearer samples, ($\kappa_{s,600} < 0{\cdot}05$) S_1 increases with decreasing values of $\kappa_{s,600}$.

From a consideration of the size scale at the bottom of Fig. 8, it would appear that most of the more turbid samples ($\kappa_{s,600} > 0{\cdot}05$) contain a preponderance of large particles with diameters in excess of 1·2 μ. On the other hand, the clearer samples with $\kappa_{s,600} < 0{\cdot}5$ must contain a higher proportion of the finer material. The clearest samples with $\kappa_{s,600} < 0{\cdot}025$ have values of $S_1 > 2{\cdot}80$, indicating a preponderance of very fine material with diameters less than 0·2 μ. A similar relationship between S_1 and $\kappa_{s,600}$ was somewhat less in the Chesapeake than in the present samples.

S_1 increased rapidly with depth for most station data (Fig. 9). All of the values of S_1 for samples from over 400 metres are greater than 2·5. The surface layer samples down to 40 m are the more turbid, and contain relatively large particulate matter. All of the clearer samples from below 400 metres contain relatively fine particulate matter, with diameters less than 0·4 μ.

DISCUSSION OF RESULTS

The general shape of the transmission curve has been shown, along with the relative transparency for a number of samples. Instrumental difficulties resulting in random fluctuations in readings indicate that the instrument used should be further modified for work at sea. One major problem would be solved by adapting the instrument to hold two long cells similar to the two short cells which are normally used in chemical work. If this were done, the sample could be examined at exactly the same wave length as the standard each time a reading is made. With the present single cell arrangement, very small errors in repeating wave length settings introduce large errors in that part of the spectrum where the combined transmission of the cell and the water medium is changing the most rapidly. The error due to wave length setting was very large at 750 mμ, somewhat less at 800 and 700 mμ, and appeared to be of less importance in other parts of the spectrum.

COMPARISON WITH SUBMARINE PHOTOMETER AND BATHYPHOTOMETER DATA

It is difficult to make a quantitative comparison between the results of this study and published transmission data based on submarine photometer and bathyphotometer readings. The hardest problem is to evaluate the photometer data in terms of the relatively wide wave length band covered by the combination of filters and photoelectric cells or photomultiplier tubes. Transmission of the water, response of the instrument, extinction due to material in the water, and the solar spectrum all vary over the wave length band considered. The problem becomes most critical at the extremes of the visible spectrum.

A second problem arises with the evaluation of the standard distilled or filtered deep water used in this study. The optical effects of the standard must be added to the spectrophotometer data or subtracted from the photometer data in order to make the two types of data comparable. The standard always contains some contamination which makes its transmission less than that of truly pure water and slightly different from other standards at all wave lengths. Due to the slight differences, the relative importance of the effects of the contamination in the standards is negligible, except in the study of the clearest oceanic samples. The transmission for distilled water reported by James and Birge (1938, Table 1) was arbitrarily selected to be used to

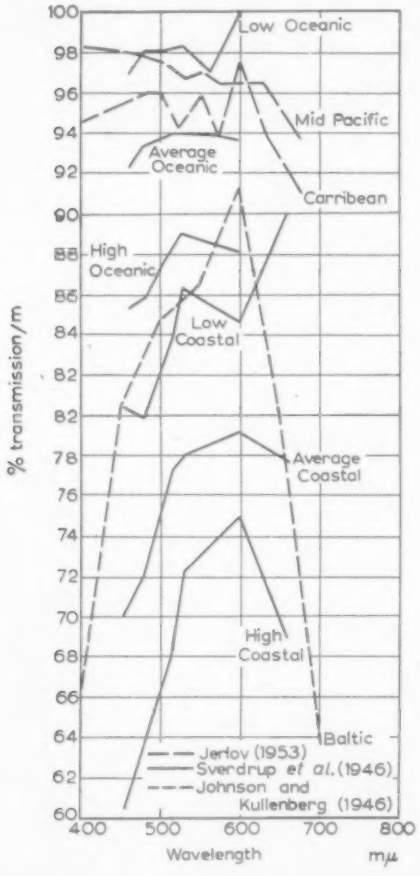

Fig. 10.

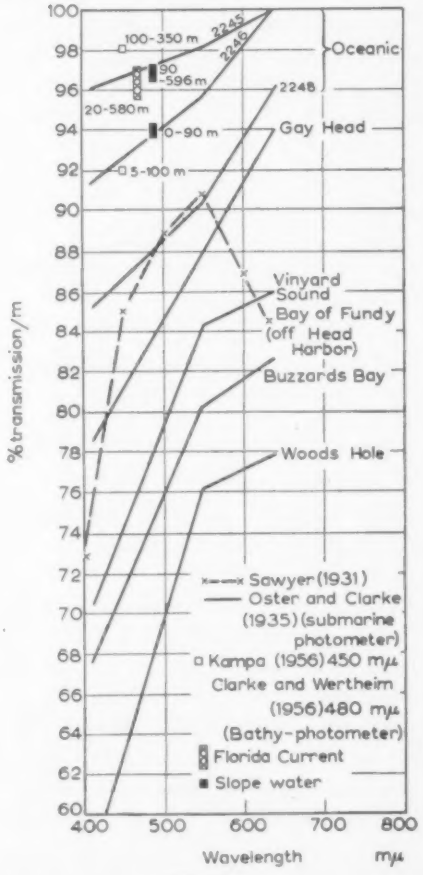

Fig. 11.

Figs. 10–11. Transmission data obtained in various regions by other researchers. The extinction of pure water has been subtracted to make these data comparable to those discussed in the text and appearing in Figs. 2 to 7, inclusive.

subtract the optical effects of the water from submarine photometer and bathyphotometer data in order to compare these data to the spectrophotometer data presented in this paper. The comparison will be in error by the relatively small unknown

differences between the standard used in this study and the distilled water which was examined by JAMES and BIRGE.

The adjusted photometer data is plotted as per cent transmission per metre in Figs. 10 and 11. The vertical per cent scale and the horizontal wave length scale is the same as those used on Figs. 2 through to 7 in order to facilitate direct visual comparison. A vertical logarithmic scale was used on Fig. 2 to cover a longer range than was needed for the rest of the transparency figures.

UTTERBACK's, (1936) data were adapted from Table 22 of SVERDRUP *et al.*, (1946) and plotted on Fig. 10. The individual curves on Fig. 10 vary considerably in shape. Transparency tends to increase with wave length on most of the curves giving the curves somewhat the same shape as those shown in Figs. 3 to 7. The range of transparency covered by the three oceanic curves is approximately the same as that for most of the surface layer waters examined in this study with the exception of the surface waters in the Peru Current near Talara and those on the equator at Station 74. Waters in these two regions were considerably less transparent than the oceanic waters examined by UTTERBACK. The transparency range for coastal waters shown on Fig. 10 is about the same as that for the surface layers at Station 74 on the equator and for the stations in the Peru Current which were over 22 miles from shore. The surface samples from Talara, Peru, and from 16 and 22 miles from Talara were considerably less transparent than the coastal waters examined by UTTERBACK.

JOHNSON (JERLOV) and KULLENBERG (1946) present a review table of spectral transmission data from submarine photometers. The curve labelled Baltic on Fig. 10 is typical of the material presented for the Baltic Sea, Swedish and Norwegian Fjords, and the English Channel. The extremely high increase in transmission with increasing wave length between 400 and 600 mμ is higher than was found on East-Tropic. It may be related to the high concentrations of " yellow substance " in solution in those waters. The large decrease in transmission with increasing wave length between 600 and 700 mμ is not in agreement with East-Tropic data. This decrease in transparency would have to be due to dissolved material with a high absorption in this part of the spectrum or a small error in the evaluation of the effective wave length of the longer wave length filters used on the instruments. For example, subtracting the extinction for water at 720 mμ from the raw data for 700 mμ would lift the point for 700 mμ from 64·6 per cent to 96·2 per cent.

JERLOV (1953) presents a table of spectral transmission data for six ocean stations. Two typical sets of these data are plotted on Fig. 10. Transmission is in the same range as that for the clearest surface samples from East-Tropic. JERLOV's data shows decrease in transmission with increasing wave length over most of the spectrum.

Parts of the data presented by SAWYER (1931) and OSTER and CLARKE (1935) and the data of CLARKE and WERTHEIM (1956) and KAMPA (1956) are plotted on Fig. 11 after the effects of the water medium have been subtracted from each datum. Wave lengths assigned to the individual points were selected after a consideration of the spectral response of the instrument used, the solar spectrum (KIMBALL, 1924), and the narrowing of the solar spectrum with depth.

SAWYER's transmission data for Bay of Fundy water is plotted as a dashed line on Fig. 11. The curve shows a rapid increase in transmission with wave length to 550 mμ and then a rapid decrease in transmission from 550 mμ to 630 mμ. The water was

clearer than either the coastal waters examined by UTTERBACK or those examined in the present study.

The transmission curves for the data from OSTER and CLARKE (1935) are based on three points. These curves show somewhat the same shape and approximately the same range in transparency as most of the transmission curves presented in this paper. Apparently, New England coastal waters have about the same transparency as the surface waters for Station 74 on the equator, but are considerably clearer than the waters of the Peru Current within 25 miles of the shore.

The submarine photometer data discussed above is restricted to the surface layers above approximately 100 m., due to the limited range of sensitivity of the photoelectric cells. On the other hand, bathyphotometer data is obtained with very sensitive photomultiplier tubes, which enables the depth range to be extended to 600 m or more. The available data is restricted to a relatively wide band in the blue end of the spectrum which narrows with depth due to the harding of the light. The results are shown on Fig. 11 for the region of the San Deigo trough off California (KAMPA, 1956) and for Atlantic Slope water and Florida Current water (CLARKE and WERTHEIM, 1956). It is interesting to note that both of these studies agree with the results of the present study in finding a surface layer of relatively turbid water over more transparent water extending from approximately 100 m down to the limit of the sensitivity of the instruments.

Acknowledgments—Thanks are due to Messrs JAMES M. SNODGRASS, ROBERT F. DEVEREAUX, and JOHN H. CAWLEY Jr. of the special Developments Division, Scripps Institution of Oceanography, and their sponsor, the Bureau of Ships, U.S. Navy, for converting the Beckman Model DU Spectrophotometer for use at sea. The author wishes to take this opportunity to thank Dr. WARREN WOOSTER for suggesting and arranging for his participation in the East-Tropic Expedition, and to especially thank Mr. TOWNSEND CROMWELL and Mr. JOHN KNAUSS, and other members of the expedition for ready assistance and cooperation in carrying out the programme at sea.

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This research was supported by Office of Naval Research Contracts with Oregon State College and Scripps Institution of Oceanography of the University of California.

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An airborne radiation thermometer

WILLIAM S. RICHARDSON and CHARLES H. WILKINS

(*Received* 23 *September* 1957)

Abstract—An airborne radiation thermometer for use in measuring sea surface temperatures from aircraft is described. Infra-red radiation from the water surface is compared to the radiation from a black body at known temperature within the instrument. The sensitivity is about 0·01°C. Errors attending such measurents are discussed, and several applications to oceanographic research are cited.

INTRODUCTION

THE determination of the surface temperature of solids or liquids by measuring the radiation emitted from them is generally called radiation pyrometry, and optical pyrometers for the measurement of high temperatures have been in use for many years. Such a device measures the difference between the radiation from the surface and the back radiation from the detecting element (generally a thermocouple). As long as the surface temperature is high compared to the ambient temperature, reasonable fluctuations in ambient temperature do not cause serious errors in such a measurement. However, to measure the temperature of a target at or near ambient temperature it is necessary to provide elaborate compensation or to use a chopped system in which the detector " looks " alternately at the target and a known temperature, comparing the two. This technique was first used in oceanography by STOMMEL and his co-workers (1953) who developed a most useful if somewhat insensitive instrument for measuring ocean surface temperatures from aircraft. The instrument described in this paper is an outgrowth of this work.

It is well known that the hemispherically radiated energy (E) from a unit area of a surface at temperature T is:

$$E = e\sigma T^4 \tag{1}$$

where e is the emissivity of the surface and σ is the Stefan–Boltzmann constant. This energy originates from a layer in the surface of thickness sufficient to give total absorption, and in the case of water at the wave lengths of interest this thickness is about 0·01 mm. Liquid water is very nearly a black body for all wave lengths beyond 1 μ in the infra-red and for the purposes of this paper we will assume $e = 1$.

The spectral distribution of the energy from such a surface is governed by the Planck distribution law and for 300°K is shown in Fig. 1. The shaded sections indicate regions of the spectrum where the energy is lost, at any reasonable distance from the target, due to absorption by water–vapour or carbon dioxide in the air path. The effect of this absorption and of emission by these substances will be discussed below. As can be seen in the figure the energy is peaked at about 10 μ in the infra-red and is transmitted primarily by a " window " in the atmosphere between 8 μ and 12 μ.

If the detector has an active area A and a responsivity R (volts output per watt of radiant energy input) and is used in an optical system of focal length f and diameter D, then the electrical signal developed from the target area on the sea will be S where:

$$S = \frac{D^2 AR\tau_1 \tau_2 \sigma T_W^4}{4\pi^2 f^2} = KT_W^4 \tag{2}$$

where τ_1 is the fractional transmission of the optical system, τ_2 is the same for the atmosphere, and T_W indicates surface water temperature. If the optical system is

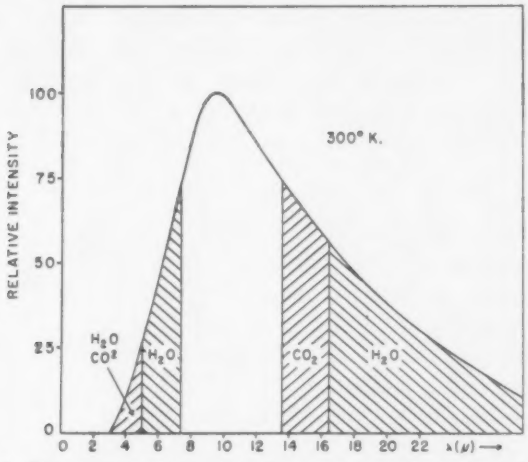

Fig. 1. The spectral distribution of energy from a 300°K black body.

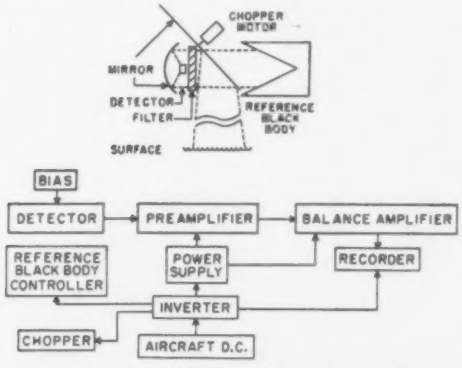

Fig. 2. Block diagram of the Radiometer.

chopped at frequency ν so that the detector sees a reference black body at temperture T_R (alternating with T_W) then the electrical signal will be AC at frequency ν with amplitude S' and:

$$S' = K(T_R^4 - T_W^4) = 4KT_R^3 \Delta T \tag{3}$$

where $\Delta T = T_W - T_R$. The last approximation holds only if τ_2 is the same in both paths and for ΔT small compared to the fixed T_R. In this case the a.c. signal amplitude is a linear function of the difference between the ocean and reference temperatures.

In general the instrument consists of a detector, an optical system, the reference black body, amplifiers and a recorder. A block diagram is shown in Fig. 2, and each component is discussed in a following section.

THE OPTICAL SYSTEM

Normally mirror optics are used in this type of system although lenses of silver chloride or arsenic trisulphide glass are also useful. In this particular instrument a first-surfaced aluminized spherical mirror of 3 in. diameter and $1\frac{1}{2}$ in. focal length is used as the focussing member. The mirror chopper is first-surfaced aluminized Plexiglas 12 in. in diameter and cut in the form of two 90° sectors with 90° openings between. This is rotated by a synchronous motor at 300 rev/min to give a chopping frequency of 10 c/s. Filters to help isolate the 8 μ to 12 μ band can be added but the cost in energy loss is quite high. Any filter must, of course, be put between the detector and the chopper so that its emission does not contribute to the a.c. signal.

THE DETECTOR

This instrument uses a thermistor bolometer as a detector (WORMSER, 1953). Thermocouples and other types of bolometers have also been used, but the rigid mounting of the thermistor flakes seems to provide better performance in aircraft than other units of comparable cost and sensitivity. (The Golay cell used by STOMMEL (1953) was very sensitive, but very microphonic in the aircraft). The detector consists of a thin flake of thermistor material 2 mm × 2 mm, blackened, and exposed to the radiation through a silver sulphide coated silver chloride window. This coating is opaque to radiation of wavelengths shorter than 2 μ and acts as a filter opening up between 2 μ and 5 μ in the infra-red; its transmission is shown in Fig. 3. An

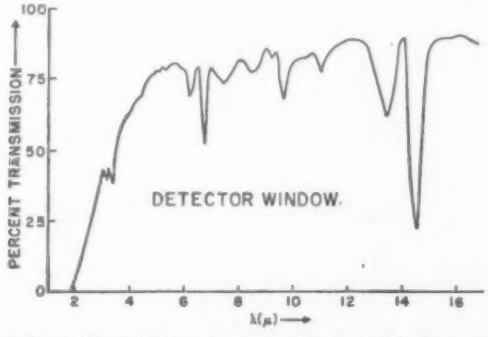

Fig. 3. Spectral transmission of the detector window. All other optical components are non-selective.

additional matched flake within the detector capsule is hidden from the radiation and provides DC balance with changing ambient temperature. The two flakes are connected as two arms of a bridge biased to ± 180 V/d.c. with small dry batteries. Since the flake resistances are about 3 MΩ the battery drain is not large, but carefully selected batteries must be used to eliminate noise at this level.

The size of the detector flake is dictated by cost and availability. The 2 mm × 2 mm size when used with the above mirror provides a target area on the sea surface of about 50 ft × 50 ft at 1000 ft altitude (and in proportion at other altitudes).

THE AMPLIFIERS AND RECORDERS

The signal which arises from the detector bridge when radiation falling on the flake changes its temperature and resistance is a 10 c/s AC voltage which is amplified by the

pre-amplifier shown in Fig. 4. The detector and bias connections are also shown. This unit is a commercial one (WORMSER, 1953) manufactured for use with the detector. It has a voltage gain of 5000 and a passband (3 dB down) from 5 to 250 c/s.

The pre-amplifier filaments are run on 12 V/d.c. transformed, rectified and strongly filtered from 115 V/d.c. The *B* voltage is supplied by a rectifier supply, glo-tube regulated at 250 V/d.c. and strongly filtered. A tap from one of the glow-tubes provides 105 V/d.c. for the balance amplifier described below.

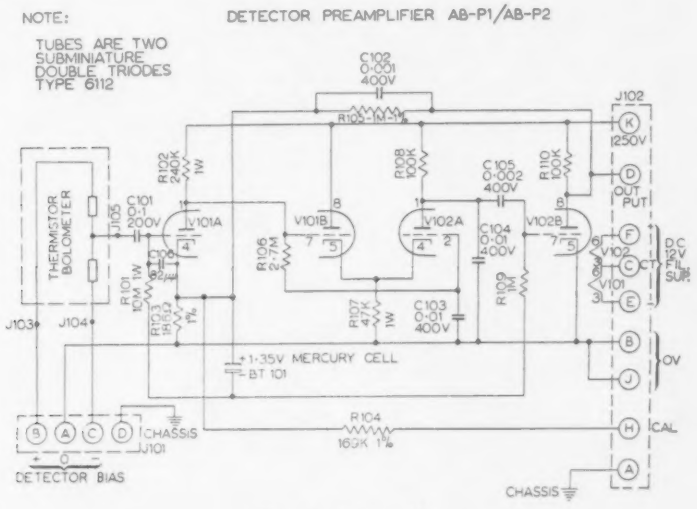

Fig. 4. Preamplifier.

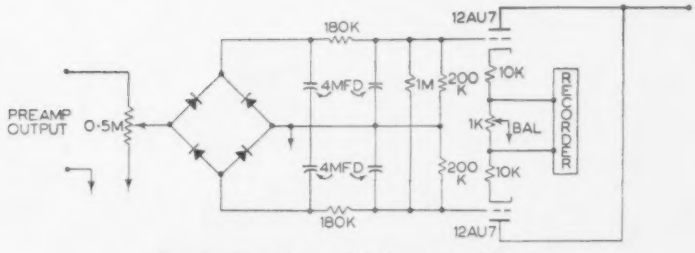

Fig. 5. Rectifier and balance amplifier.

The a.c. signal from the pre-amplifier is divided by a potentiometer for gain control and rectified by a full-wave silicon diode bridge. The d.c. output of this bridge is then filtered to remove the chopping frequency and passed to a balanced cathode follower circuit as shown in Fig. 5. The output of this balance circuit drives the recorder.

The recorder may be any commerical unit of either the self-balancing potentiometer or d.c. amplifier-recorder type. For most purposes a sensitivity of the order of 50 mV full-scale in the recorder eliminates the need for additional d.c. amplification after the pre-amplifier.

THE REFERENCE BLACK BODY

The choice of the form of reference black body is dictated by convenience and the exactness required in the reference temperature. A water surface may be used and this

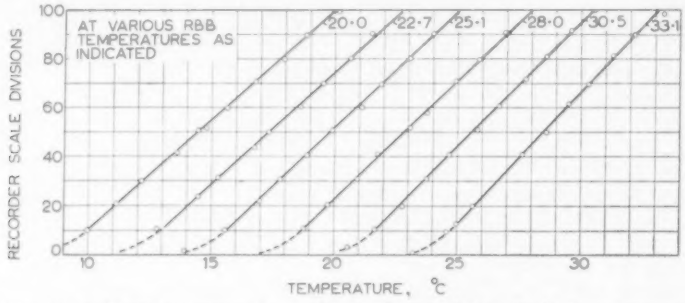

Fig. 6. Calibration curves for various reference black body temperatures.

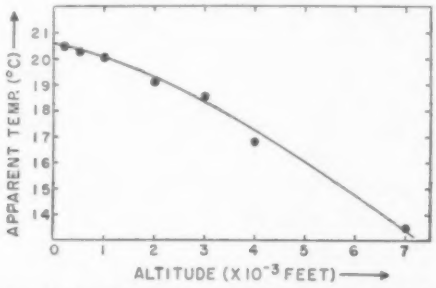

Fig. 7. Apparent temperature of Gulf Stream water off Cape Hatteras on December 20, 1956, as a function of flight altitude.

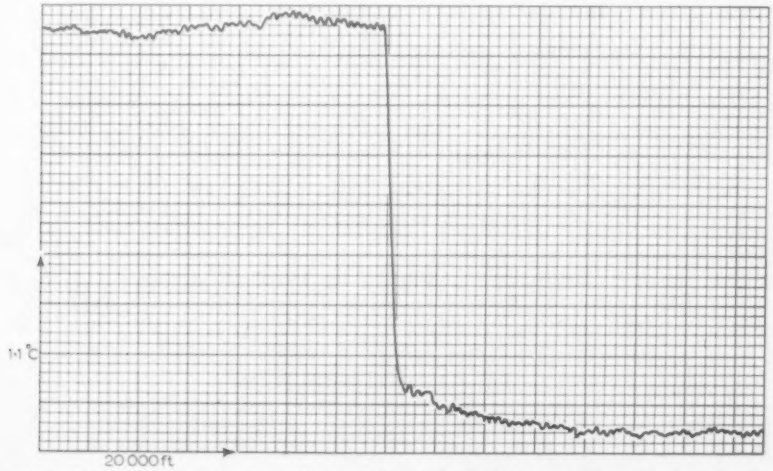

Fig. 8. Typical signal obtained on crossing the edge of the Gulf Stream (Cape Hatteras December 20, 1956; altitude 1000ft). The higher frequency oscillations were the result of a temporary instrumental difficulty.

provides very simple reference for laboratory work. It is somewhat inconvenient for work in the aircraft. In the latter case some type of thermostated blackened cone is

generally used. This should have a base (open end) somewhat larger than the diameter of the focusing element and an apex angle of less than 30°. Two forms of this have been used successfully with this equipment. The first is a thin walled brass cone wrapped with heating wire on the outside and having a small bead thermistor at its apex. The thermistor senses the cone temperature and controls it by means of a simple electronic proportional controller which feeds power to the heater windings. This arrangement will hold the cone temperature to about $\pm 0{\cdot}1°$ around the set temperature. A similar form of reference black body consists of a box with the thin-walled cone in one face. The box is oil-filled and thermostated with the same type of proportional controller. The oil is stirred and its temperature is measured with another thermistor which is part of a Wheatstone bridge, the output of which is fed to one channel of a two-channel recorder. The other channel of the recorder is used for the radiometer signal so the ocean temperature signal and the reference temperature signal are recorded side by side. The oil bath is controlled to about $\pm 0{\cdot}02°$ around the set temperature, and any fluctuations in it (which will also be fluctuations in the radiometer signal) are immediately apparent. An open oil bath of much smaller volume and similarly stirred and thermostated has been used recently. The optical system " looks " at it by means of a 45° mirror. This has proved to be the most satisfactory method to date, and the calibrations shown in Fig. 6 and the records in Fig. 8 were obtained with it.

The use of a null system in which the reference temperature is rapdily changed to follow the sea temperature to keep the detector output null would be desirable. However, no black body has yet been made tht can be controlled fast enough to keep up with the rapid fluctuations in ocean temperature which are often encountered. The reference temperature may be set close to the average of the temperatures encountered and the small fluctuations above and below this level recorded. This requires some type of phase detection to tell whether the signal corresponds to hotter or colder than the reference.

Of course, all of the reference black bodies described above will only operate above the aircraft ambient temperature. For lower ocean temperatures an ice bath may be used as the reference.

OPERATION AND CALIBRATION

With the mirror chopper stopped, no signal appears at the recorder and the balance control in the cathode follower balance circuit is used to zero the recorder at the desired point on the scale. The gain is then set up to give the desired sensitivity as observed when the instrument looks at a pan of water and the water temperature is varied. When this gain is roughly set to the desired level a more careful calibration is made and then the chopper stopped. A reproducable calibration signal consisting of a small 60 c/s a.c. voltage or a 10 c/s signal obtained from chopping a light and photocell with the mirror is then fed into the pre-amplifier and the deflection noted. This signal is then used whenever it is desired to reset the gain control to reproduce the sensitivity setting at which the calibration was made. The actual temperature of the reference black body is determined by adjusting the water pan temperature to null the signal (as observed on an oscilloscope). A typical calibration curve is shown in Fig. 6. This procedure is repeated at any reference temperature which it may be desirable to use in the field.

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ERRORS

The instrument is subject to a variety of errors which it is well to bear in mind. If the instrument is used off null as described above the signal amplitude is roughly proportional to the detector bias voltage. Thus the calibration will change as these batteries run down. Generally the batteries become noticeably noisy before their voltage falls very low, but the calibrations must be rechecked periodically (once a month or so) to check for decaying bias voltage.

The other errors which interfere with absolute temperature measurements in flight are associated with the atmosphere and the reflection of solar radiation from the sea surface. When the aircraft is banked sharply into the sun's glitter path (on a clear day with medium sun angles) a signal is observed corresponding to an apparent temperature increase of about 1°C. These signals arise from reflected radiation in the visible and very near infra-red portion of the spectrum passing the detector window filter. It is easily demonstrated that there is not sufficient long wave length solar radiation in the nominal pass band of the filter to account for the signals. This interference disappears at normal incidence and is not ordinarily troublesome.

Absorption of part of the radiation emitted by the sea surface by atmospheric water-vapour and carbon dioxide is a more serious problem. Water-vapour shows strong absorption between 5 μ and 7 μ and carbon dioxide has a strong band from 14 μ to 16 μ; the wings of these bands delineate the ends of the 8 μ to 12 μ " window." The molecules emit radiation at the air temperature in the regions where they absorb radiation from the sea surface. These effects are difficult to compute. For the present we must be satisfied with empirical comparisons between the radiation thermometer and contact water temperature measurements. As a typical case we may consider a clear day with the humidities normally encountered in sub-tropical (tradewind) areas. When flown at 1500 ft the instrument is generally in error by about 1°C, with a proportionally less error as the altitude decreases. Equally large errors may be expected in areas where the water-vapour content is less but the difference in air–sea temperature is larger. Fig. 7 shows the apparent temperature at a fixed location in the Gulf Stream off Cape Hatteras as a function of altitude, up to 7000 ft. A quantitative empirical approach to the problem of atmospheric transmission and emission will be the subject of a later paper.

The observed random noise on the recorder corresponds to about 0·02°C. This agrees well with the figure calculated from equation 2 estimating τ_1 and τ_2 both equal to 0·5 and taking the manufacturers' values for R (200 V/W) and the observed equivalent noise input of 2 μV as the minimum detectable signal. The electronic circuit is very stable with respect to drift, but slow variations in the reference black body temperature will cause a correspondingly slow drift in the temperature record. This is eliminated in the two-channel recording system mentioned above. It must, of course, be borne in mind that this sensitivity (0·02°C) to gradients in the ocean surface deteriorates as the atmospheric absorption increases. Thus it is possible to detect a large thermal gradient such as that occurring at the edge of the Gulf Stream from several thousand feet, but the apparent amplitude of the change decreases with altitude. For general survey work and tracking the edge of the Gulf Stream (VON ARX and RICHARDSON, 1953; VON ARX, BUMPUS and RICHARDSON, 1955) it is customary to fly at 1000-1500 ft and accept the attendant errors. It is then possible

to make a low pass with the aircraft to obtain a more exact absolute temperature at any particular place.

APPLICATION OF THE INSTRUMENT

Use of an airborne radiation thermometer in tracking the edge of the Gulf Stream has been described elsewhere (VON ARX and RICHARDSON, 1953; VON ARX, BUMPUS and RICHARDSON, 1955). A typical record of the temperature gradient across the edge is shown in Fig. 8. The instrument has been used to detect small changes in the surface temperature which occur in the trade wind areas (MALKUS, 1957) (Fig. 10).

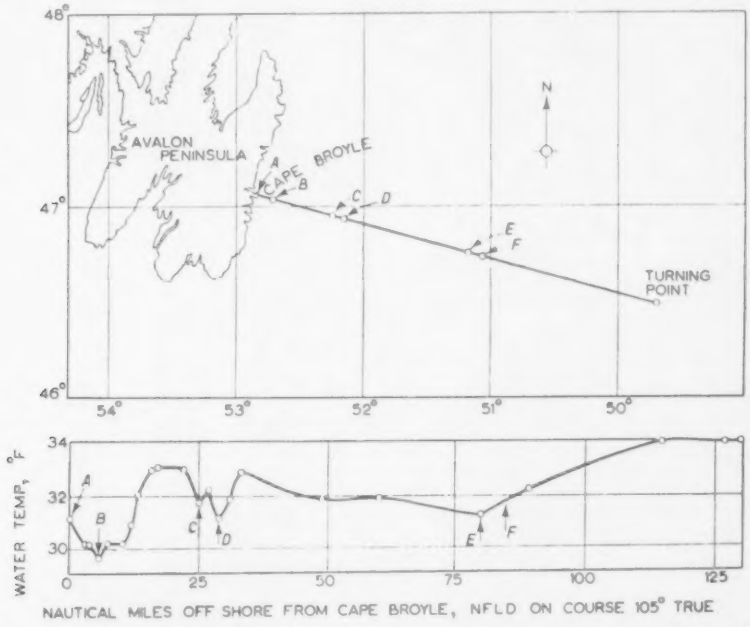

Fig. 9. Surface temperature measurements on a course inbound to the Avalon Peninsula of Newfoundland showing two bands of cold water near the Coast.

There are a variety of oceanographic and limnological problems where surface temperatures provide a good indication of the processes which are occurring. The aircraft by virtue of its speed and its ability to reach normally inaccessible places is often the only vehicle which may be used. Also the high speed provides a degree of synopticity which is not achievable with ships. Figs. 8, 9 and 10 show some typical results.

Acknowledgements—The authors are indebted to the United States Navy Bureau of Aeronautics (Contract No. NOas 55-401-c) and Office of Naval Research (Contract No. Nonr-1367(00)) for support of various phases of this work. Suggestions from and assistance by our colleagues at the Woods Hole Oceanographic Institution are also gratefully acknowledged.

Woods Hole Oceanographic Institution. Contribution No. 934.
from the Woods Hole Oceanographic Institution.

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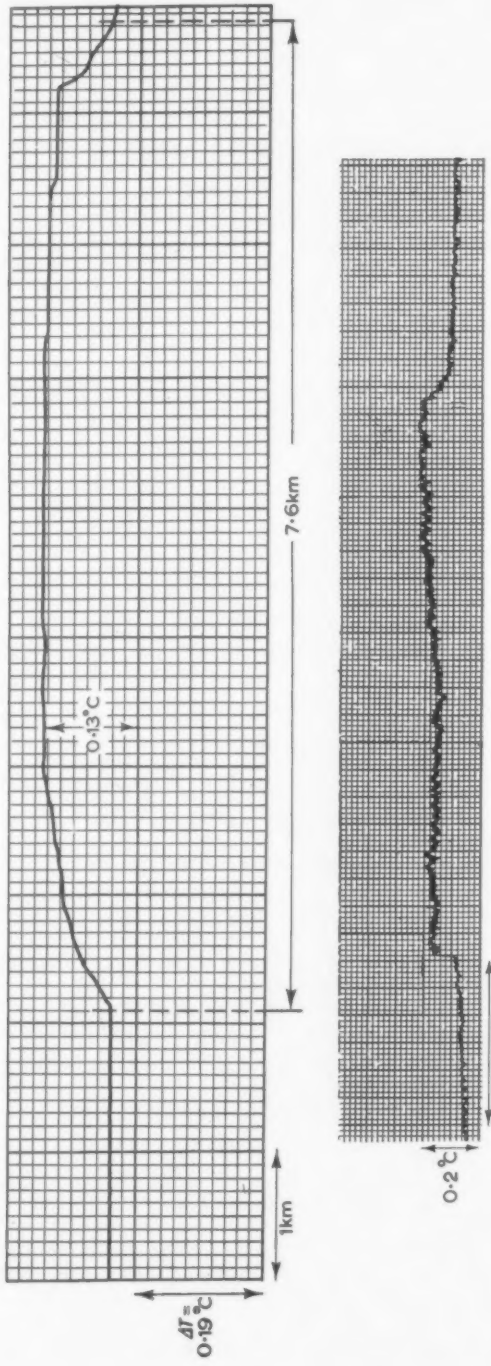

Fig. 10. The upper record is a warm patch north of Jamaica in April, 1956. The lower trace is a similar patch recorded by a contact thermometer on the R/V *Atlantis* in the same area on the same day.

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The Sea Past and Present

(A congress review)

THE "Geologische Vereinigung" held its Annual Congress at Wiesbaden (Western Germany) on 15-18 March 1957 with the theme: "Das Meer in Gegenwart und Vergangenheit" (The Sea Past and Present). This association founded in 1910 has a general theme for its Annual Congress allowing a many-sided treatment. Due to the International character of the association, lectures are given in English, French, or German. The papers will be published as articles in "Geologische Rundschau" in English, French, or German. Each issue of "Geologische Rundschau" ends with a short summary in English and in French of all articles. The lectures of the congress will be published as issue 1 of Vol. 47 in 1958.

The Congress of Wiesbaden wished to present the activity and picture of present seas compared with fossil evidence of ancient regions of the sea. Therefore a discussion was possible between oceanographers, marine biologists, sedimentologists, geologists of different sections (especially submarine geology) and interested scholars of other sciences.

Knowledge of geology and palaeontology in many cases is taken from the study of fossil marine products. Most palaeographical or stratigraphical research cannot be made without a knowledge of marine sediments. Most of the known fossil marine sediments are those from shallow seas, but we have answers to many questions about the deep sea also. Therefore Ph. H. KUENEN, Groningen demanded in his lecture ("No geology without marine geology") an intensive use of submarine research results for geology. In the deep sea there are special problems arising out of general questions on sedimentation i.e. turbidity currents. But there are also other great problems: oscillation of sea-level, submarine volcanism and many geophysical questions. (Some of the latter were discussed at the Annual Congress of 1956 of "Geologische Vereinigung" with the theme: "Geologie und Geophysik der Tiefen" (Geology and Geophysics of the depth of the Earth), published in issue 1 of Vol. 46 of "Geologische Rundschau," 1957).

A few lectures gave information on the many-sided problems of modern marine research. R. S. DIETZ, London showed a picture of the deep sea floor with surprising moments in its great and little forms ("The deep sea floor: a review of postwar research in the U.S.A.").

For studying profiles in the deep sea floor it is necessary to have instruments of great precision for taking samples. B. KULLENBERG, Göteborg ("Technik der Gewinnung von Tiefseesedimenten") gave information on some instruments especially of the "Kolbenlot." With it one can take samples of deep sea floor sediments having a length of about 20 metres.

Some essential questions of marine streams were discussed in the lecture of W. HANSEN, Hamburg ("Der Einfluss der Gestalt der oceanischen Räume auf die Bewegung der Wassermassen"). He showed the relationship between the form of the coast and depth of the sea to movement of the water. The question of the water's movement and transport of floor sediments not only from well known shallow seas, but particularly from the deep sea was discussed by using results which G. WÜST, Kiel had placed at the disposal of this congress. In the deep sea occurred not only undisturbed sedimentation, but in many places also the transport of materials with changing length of transporting ways and different quantity of transported sediments.

There is also a difference in the kind of transport. O. MELLIS, Stockholm ("Zur Entstehung des Tiefseesandes im Atlantischen Ozean") interpreted, i.e. sandy layers in deep sea sediments of the Atlantic ocean hardly as a product of marine streams, but originated by movements of sediments on occasion of tectonic occurrences.

On the other hand special currents and with them different kinds of sedimentation are possible on submarine swells. This was demonstrated by J. JARKE, Hamburg ("Sedimente und Mikrofaunen im Bereich der Grenzschwelle zweier ozeanischer Räume, dargestellt an einem Schnitt über den Island-Färöer Rücken (Nordatlantischer Ozean-Rosengarten-Europäisches Nordmeer") using measurements of the German Fishery Research Ship *Anton Dohrn*. The Atlantic side of this swell is preponderantly covered by psammitic sediments to the depth of 1600 m and more, while the other side, turned to the European northern sea, preponderantly carries pelitic sediments. Temporary

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overflowing bottom-water of the European northern sea was observed by hydrographic research. These waters fall down like cascades on the southern side of the swell with an observed velocity of up to 50 cm/sec. This corresponds to the distribution of sediments, temperature of water and distribution of foraminiferous remains in the bottom sediments.

E. NORIN, Uppsala ("The sediments of the central Tyrrhenian sea") found in these sediments hints of determinable volcanic activity on land. Turbidity current deposits in profile, moreover, point out a seismical activity at this time.

A public lecture of M. PFANNENSTIEL, Freiburg/Breisgau reviewed skill and problems of submarine geology (" Eine Tiefsee-Expedition im östlichen Mittelmeer ").

In contrast to deep sea phenomena the shallow sea relatively near to land clearly shows much more influence from land. So G. MÜLLER, Celle (" Die rezenten Sedimente im Golf von Pozzuoli (Neapel/Italien) ") shows the complete dependence of sedimentation from sediment-bearing processes on land in a small simply constructed sea basin without disemboguing rivers and mostly surrounded with land. A nearly ideal distribution of the mostly volcanogenic sediments results here.

Research of E. SEIBOLD, Tübingen (" Meeresgeologische Untersuchungen in der mittleren Adria ") on sediments in a creek almost completely separated from the open sea on the isle of Mljet/Yugo-Slavia allowed an interpretation of year-bedding (" Jahresschichtung "), history of flora and anything pertaining to the first rates in the formation of petroleum-like substances.

K. GRIPP, Kiel (" Rezente und fossile Flachmeerabsätze petrologisch betrachtet und gedeutet ") started from the relations in the Baltic. Here by the action of glaciers of Würm-glaciation no older marine sediments are resting and the weak tides are without importance for sedimentation. The author pointed out the great importance of the boundary between short (time) – suspending (corresponding only to water's capacity of holding) and long (time) – suspending materials (everywhere in water). Those boundaries found in fossil sediments possibly give oceanographical interpretations, i.e. to establish oscillations of the sea-bottom or sea-level a.s.o. in geological times. It is also possible to say something of formation of cyclical sediments in connection with palaeoclimatological research.

D. NOTA (TJ. H. VAN ANDEL, W. KOLDEWYN und D. NOTA, Utrecht und Wageningen: " Ergebnisse der beiden Orinoco-Shelf-Expeditionen ") gave results of the two Orinoco-Shelf-expeditions with a great number of interesting specialities in material transport and formation of sediments in this northern part of the South American coast. R. S. DIETZ, London showed an interesting film of American submarine bottom-research by divers accustomed to oil prospecting.

Another group of lectures dealt with the coastal regions of the sea. Here E. GROBA, Berlin (" Methodische und regionale Ergebnisse einer Seegrundkartierung zwischen Falster und der deutschen Küte ") showed the dependence of sedimentation on marine streams, waves and relief of the sea-bottom. K. VOLLBRECHT, Berlin (" Das Verhalten von Meeren und Inseln gegenüber der Einwirkung des exogenen Kräftefeldes ") analyzed coastal variations in a breakers zone. G. LUDWIG, Berlin (" Beitrag zur Frage des Gleichgewichtes im System Düne-Strand-Vorstrand ") interpreted sediments in a system sandhill-beach-zone immediately near the beach. Three other lectures dealt with problems of " oblique bedding," the two latter also using fossil forms. (H. E. REINECK, Wilhelmshaven: " Longitudinale Schrägschichtung im Watt." W. NIEHOFF, Krefeld: " Eine neue Methode zur paläogeographischen Auswertung von Schrägschichtungsgefügen." P. WURSTER, Bonn: " Kreuzschichtungskörper in Flussablagerungen und in Gezeitenablagerungen ").

Most lecturers used results of sedimentpetrographical research thus underlining the great importance of this science for geology in general and especially for submarine geology. To point out this fact clearly, " Geologische Vereinigung " conferred its " Gustav-Steinmann-Medaille " on Prof. Dr. C. W. CORRENS, Göttingen in recognition of his fundamental work in sedimentpetrography especially in the scope of the Meteor-Expedition. The work of C. W. CORRENS is so important for geology because of his endeavours to establish a strictly scientific connection between Mineralogy and Geology. Knowing this " Geologische Vereinigung " has published in its " Geologische Rundschau " (Vol. 43 Issue 2, 1955) the lectures of the fourth International Congress of Sedimentology at Göttingen 1954, then conducted by C. W. CORRENS.

Research of marine biology received a hearing with two lectures. A. REMANE, Kiel (" Die biologischen Grenzen Meer/Süsswasser und Meer/Land ") discussed the boundaries of sea-fresh water and sea-land with biological methods. These questions are also of great importance for geology and palaeontological evolution. He showed a greater faunal exchange between land and sea than

one can estimate on account of the extreme conditions of life on beach. This will be especially clear also when viewing coastal groundwaters. But for some time the deep sea has also caused much interest in questions of palaeontology and evolution, for there are relics of old faunal groups. In the deep sea there was found an interesting coelacanth **Latimeria**, but there was also found earlier a representative of the invertebrates. This " living fossil " was presented in its anatomy and importance to evolution by H. LEMCHE, Copenhagen (" **Neopilina galatheae**, ein rezenter Tiefseevertreter der Kambro-Silurischen Molluskengruppe Tryblidiacea "). Ten of these little roundish molluscs were dredged by the Danish sea research ship *Galathea* from a depth of 3590 m near the western coast of Central America. Similar questions are discussed in Issue 1 Vol. 45 (1956) of " Geologische Rundschau," where the lectures of Annual Congress 1955 of " Geologische Vereinigung " at Mainz are published under the general theme : Erde und Leben (Earth and Life).

Most of the lectures mentioned parallels or contrasts marine events to-day and those of sea basins in geological times. Naturally this fact was also seen in the geological themes, whether in questions of palaeontological-biofacial problems or universal sedimentology. On the basis of palaeontology M. LECOMPTE, Brüssel (" Les récifs paléozoique en Belgique "), M. G. RUTTEN, Utrecht (" Detailuntersuchungen an gothländischen Riffen "), U. JUX, Köln (" Aufbau und Verbreitung der Riffe Gotlands ") and M. GWINNER, Stuttgart (" Schwammbänke, Riffe und submarines Relief im Oberen Weissen Jura der Schwäbischen Alb (Württemberg) ") have made research on fossil biogenic reefs. Also made with palaeontological methods were the results of K. SDZUY, Frankfurt/Main in cambrian shists (" Tiergeographische Differenzierung innerhalb des europäischen Kambriums "). Analyses of certain geological objects or regions by sedimentpetrographical or petrofacial, also geochemical, methods were shown in the following lectures : M. KSIAZKIEWICZ, Krakau (" Sedimentation in the Carpathian Flysch Sea "). R. F. RUTSCH, Bern (" Faziesprobleme der voralpinen Molasse "). W. ZEIL, München (" Sedimentation in der Magallanes-Geosynklinale mit besonderer Berücksichtigung des Flysch "). R. BRINKMANN und E. DEGENS, Bonn (" Geochemisch-biofazielle Untersuchungen im Ruhrkarbon "). H. J. SCHNEIDER, München (" Sedimentäre Blei-Zink- und Fluoranreicherungen als fazielle und episodische Sonderentwicklung in der permotriassischen Geosynklinale der Ostalpen "). L. GREILING, Würzburg (" Die Kieselschiefer des Frankenwaldes "). D. RICHTER, Münster (" Verbreitung und Gesteine der Arosazone zwischen Mittelbünden und dem Allgäu ").

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H. MURAWSKI

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REPORT OF MEETING

Special Committee on Oceanic Research

THE first meeting of the Special Committee on Oceanic Research of the International Council of Scientific Unions was held at the Woods Hole Oceanographic Institution from 28 August to 30 August 1957.

The following members were present :

Dr. A. FR. BRUUN	Denmark
Dr. G. BÖHNECKE	Germany
Commander L. R. A. CAPURRO	Argentina
Dr. G. E. R. DEACON	U.K.
Dr. M. N. HILL	U.K.
Dr. C. O'D. ISELIN	U.S.A.
Dr. N. B. MARSHALL	U.K.
Dr. Y. MIYAKE	Japan
Prof. H. MOSBY	Norway
Dr. N. W. RAKESTRAW	U.S.A.
Dr. R. REVELLE	U.S.A.
Prof. E. STEEMANN NIELSEN	Denmark
Prof. L. ZENKEVITCH	U.S.S.R.

Those unable to attend were :—

Prof. Y. LE GRAND	France
Dr. N. K. PANNIKAR	India

The Director of the Woods Hole Oceanographic Institution, Dr. C. O'D. ISELIN took the chair for the meeting. Dr. R. FRASER, Administrative Secretary of I.C.S.U. and Dr. R. L. ZWEMER, National Sciences Department of U.N.E.S.C.O. also attended the meeting.

The following is the report resulting from this meeting which was adopted by the Bureau of the International Council of Scientific Unions at their meeting in New York in September 1957.

There are three long range problems of the oceans that may be of critical importance to the future welfare of mankind.

The first of these concerns the use of the deep sea as a receptacle for the waste products of our industrial civilization. This may be a particularly important problem in the future, when very large quantities of poisonous radioactive wastes will be produced by the industrial use of atomic power. We need to know whether we can dispose of at least part of these wastes in the deep sea or whether the oceanic circulation or the vertical movements of these fauna will results in too rapid a transport of dangerous material to levels in the sea from which the world's food supplies are in part derived.

The second problem is concerned with the oceans as an important source of protein food for many of the world's peoples. With the quick growth of populations, man's need for food from the sea may be expected rapidly to increase. The living resources of the oceans are by no means infinite and like the land different parts differ widely in fertility. The fertile areas are those where nutrient trace substances, essential for plant life, are brought up from the deep waters. To obtain the maximum harvest, we must understand the processes by which this occurs.

The third important problem is perhaps the least well understood of the three. It concerns the role of the oceans in climatic change. During the last fifty years the average temperature over eastern North America and northern Europe has markedly increased, while elsewhere prolonged draughts have destroyed the work and hopes of decades. Will this trend continue over the next fifty years, or will it be reversed ? Because we do not have sufficient understanding of the processes that control climate, we are quite unable to make a forecast. Nevertheless a prediction of future climate would be of inestimable value to society.

It is probable that the waters of the oceans play a major role in changing climates. For example, an excess of heat from the sun can be stored in the deep water and slowly released over many years to warm the air. Likewise the amount of carbon dioxide in the air, controls at least to some extent, the average air temperature and the loss of heat from the earth. Any change in the atmospheric carbon dioxide, for example by the addition of that provided from fossil fuel combustion may be damped or modified by the absorption of carbon dioxide in the ocean waters.

For all three of these problems greater knowledge is required of the rate and character of the exchange between the deep and surface waters of the oceans. It is only within the last few years that we have been able to make an effective attempt to gain such understandings and three lines of approach are now being used. They are, (1) theoretical analysis of the thermodynamics and hydrodynamics of the oceans, (2) laboratory and field experimentation with indirect techniques, and (3) the development and field use of new instruments and techniques for the direct measurement of the deep and shallow currents of the oceans.

The physical difficulties of making such measurements have only in part been overcome. Among the new techniques becoming available are the following : (1) The use of natural radioactive substances occurring in the water, such as radio-carbon and tritium to trace the paths of motion and the mixing of the waters. (2) Means for the direct measurements of the deep currents, by following free-floating neutrally buoyant buoys or by using deep current meters. For these techniques, it is necessary to maintain a fixed reference position and this can now be achieved by tautly anchoring a surface buoy to the sea bottom. (3) the measurement with a new order of precision of the salt content of the water. This allows the salt to be used as a tracer of the water movements. (4) The measurement of the heat flow from the interior of the earth into the deep water, which allows the heating of the deep water to be used as an index of the time of passage of the water over the bottom. (5) The possible introduction of relatively large amounts of artificially radioactive substances, of the order of tens of thousands of curies or more, into deep ocean areas. In principle, the dispersion and transport of this material by the deep currents could be followed over an extended area for a significant length of time. (6) Detailed biological, chemical and physical studies of the variations in the sediments of the deep-sea floor, to decipher past changes in the water conditions. (7) New methods of high precision for determining the carbon dioxide in the water and the air.

The Special Committee on Oceanic Research considers that its principal objective should be to encourage and co-ordinate an international programme of observation and measurement of the deep ocean waters. One point of this programme would involve an intensive effort to understand the relationship between the plants and animals with that of the dynamics of the upper water layers. The other would be a study of the region below the thermocline down to the greatest depths of the sea and of the deep-sea floor itself. Because so little is known about this latter region, its investigation will be to a large extent, a task of widespread exploration. It must proceed hand in hand with theoretical studies and development of new techniques by individual scientists in the laboratory, and must supplement rather than interfere with their work.

Deep-sea exploration, because it involves the use of relatively large and heavily equipped ships for long periods, is the most expensive kind of oceanographic research. An adequate programme of exploration is beyond the resources of any one country. Moreover, the total cost will be minimized through planned international co-operation in the use of ships and facilities.

Such a programme of international co-operation in deep-sea exploration will have several aspects; (1) For the first two or three years the principal effort will be devoted to the exchange and standardization of techniques in all the branches of marine science, the collection of samples for analysis and study by different laboratories and the exchange of data that can serve to guide further explorations. During this stage of development this effort will necessarily be concentrated in the North and South Atlantic and the North and South Pacific oceans. Considerable financial support is needed to carry on the task of adequately detailed measurement over these vast areas. (2) With adequate preparation during the first two or three years it would be possible during the third or fourth years, provided sufficient funds and ship time become available, for as many as sixteen ships from many different countries to make a combined assault on the largest unknown area on earth, the deep waters and sea-bed of the Indian Ocean. Apart from this area being practically unexplored it is of great general interest to the physical oceanographers since the seasonal reversals in wind direction, unknown elsewhere, will provide better understanding of how the wind driven currents of the oceans of the world are built up. Likewise for its unique qualities it will provide valuable evidence for those

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investigating the general productivity of the oceans. Few scientific people have ever visited this area and almost none of the new techniques have been applied there. It would be anticipated that in addition to scientists from the Northern Hemisphere, scientists and students from the countries bordering on the Indian Ocean would take part in this series of simultaneous expeditions. Thus, the expeditions would not only serve their primary purposes of exploration, but would have a lasting effect in encouraging and developing the marine sciences and fisheries in those countries. (3) During the following years, when the presently severe difficulties of making measurements and observations at depths of several thousand meters and of obtaining accurate positions on the high seas have been effectively overcome, a tracer experiment, using a large quantity of artifically radioactive material, should be undertaken in some suitable deep-sea area. This will involve very careful planning and co-ordination.

The programme of deep-sea research, development, and standardization outlined above cannot be carried out successfully without the enthusiastic support of other national and international organizations of marine science. Every effort should be made to utilize their already existing facilities and procedures. Moreover, it will be necessary not only to obtain financial support for individual ship operations of the different countries taking part, but also an adequate budget must be made available to S.C.O.R. itself, (1) to pay for meetings of working groups of specialists who are developing and standardizing new techniques, and who are planning new explorations, (2) to establish a secretariat to maintain a flow of information about new methods, designs of instruments, and plans among the different countries, and (3) to allow transfers of key scientific personnel to the laboratories and ships where they can train, or learn from others, the use of specialized techniques and methods.

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FINANCIAL REQUIREMENTS

In the initial stages of its programme S.C.O.R. considers that the following annual and non-recurrent expenditure would be involved. The annual expenditure should in the first instance, continue for a minimum period of 5 years.

(1) *Annual budget*

Executive secretary and typists and office rent	$7,500
Travelling expenses for S.C.O.R. and executive committee	$7,500
Travelling expenses for 5 working groups	$20,000
Travelling and subsistence expenses for 4 observers a year visiting to teach or learn new techniques	$10,500
Annual expenditure	$45,500
Total for 5 years	$227,500

(2) *Expenditure on Indian Ocean exploration*

Cost of say, 16 ships each operating in the Indian Ocean for 8 months	$2,400,000
Training of 25 scientists from Indian Ocean area, each for one year at $3,000 per head	$75,000
Special equipment for each ship at $24,000	$384,000
Salaries of the scientists working in the ships (100 people for 1 year)	$550,000
Working up the scientific results (100 people for 1 year)	$600,000
Publication of results	$30,000
Total cost	$4,039,000
Less estimated contribution from normal operating costs and salaries	$2,000,000
Estimated extraordinary cost	$2,039,000

It was suggested that Oceanographic ships for exploration in the Indian Ocean might be provided by the following nations :— Argentina, Australia and/or New Zealand, Denmark, France, Germany, India and/or Pakistan, Japan, Thailand, United Kingdom, U.S.A. and U.S.S.R.

S.C.O.R. recommends that the following working groups, of perhaps 5-7 members each should be formed,

(1) The measurement of artificial radioactivity.
Convener : Dr. Y. MIYAKE Japan

(2) The measurement of the CO_2 in the air and sea and its exchange rate.
Convener : Prof. N. W. RAKESTRAW U.S.A.

(3) The measurement of the standing crops and productivity of the sea.
Convener : Dr. N. B. MARSHALL U.K.

(4) The measurement of the physical properties of sea-water.
Convener : Prof. H. MOSBY Norway

(5) The exploration of the Indian Ocean.
Convener : Dr. C. O'D. ISELIN U.S.A.

The Committee recognized that there might later be a need to subdivide Group 3.

S.C.O.R. recommends that the following nominations be accepted by I.C.S.U. :

Chairman of S.C.O.R. :	Dr. R. REVELLE	U.S.A.
Vice-Chairman :	Dr. G. E. R. DEACON	U.K.
Secretary	Dr. G. BÖHNECKE	Germany
Finance Committee :	Dr. C. O'D. ISELIN	U.S.A.
	Prof. L. ZENKEVITCH	U.S.S.R.

It was agreed that the next meeting of S.C.O.R. should be held at Hamburg, late July or early August, 1958.

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LETTERS TO THE EDITORS

Letters concerning "Fossil land shells from deep drill holes of the Pacific atolls" H. S. Ladd and J. I. Tracy, Jr. (Deep-Sea Res., 4, 218-219).

Comment on a paper by Ladd and Tracey

(*Received November* 2, 1957)

In a letter (*Deep-Sea Res.* (1957) **4**, 218-219) H. S. Ladd and J. I. Tracey, Jr. report on "Fossil land shells from deep drill holes on western Pacific atolls." This is an extremely interesting result confirming an earlier conclusion based on leached zones.

Perhaps a different suggestion may be offered instead of the two possibilities for explaining the emergence which they mention: ". . . . either an eustatic movement for which there is not other known evidence, or an uplift of the sea floor on a scale large enough to encompass islands 200 miles apart." Presumably they mean that these movements amounted to the present depth of about 1100 ft. It is not much more probable that most atolls are situated on subsiding foundations and that small eustatic movements have caused temporary emergence? Obviously one could not expect to find any evidence elsewhere of such a slight eustatic movement.

It has been suggested long ago by Molengraaff that each volcanic cone on the deep-sea floor tends to sink in consequence of its positive isostatic anomaly. I have pointed out that the rate of sinking is extremely small (1954). Hence one may assume that reefs normally reached to the breaker zone, a supposition supported by the absence of deep passages in the coral seas. If this is accepted only a slight eustatic shift would suffice to cause emergence until waves and solution has removed the emerged part. There would be ample time for weathering and population. Although the rate of subsidence may be roughly equal in many cases there is no reason to doubt that if a Miocene eustatic movement affected most reefs of that time, these horizons will now be situated at various levels.

University of Groningen, Netherlands. Ph. H. Kuenen

REFERENCE

Kuenen Ph. H. (1954) Eniwetok drilling results. *Deep-Sea Res.* **1**, 187-189.

Reply to Kuenen's letter

(*Received December* 5, 1957)

As noted by Kuenen in the opening sentence of his comment, the discovery of fossil land shells in drill holes beneath atolls does offer confirmation of our earlier conclusions based upon leached zones containing molds of aragonite-secreting organisms. Kuenen then suggests an alternative explanation of the leached and recrystallized zones, including the one now found at about 1100 ft beneath Bikini and Eniwetok. His alternative is that ". . . most atolls are situated on subsiding foundations, and that small eustatic movements have caused temporary emergence." This over-simplifies the problem.

In the central Pacific, atolls are indeed situated on subsiding foundations, as has been demonstrated by drilling on Funafuti, Bikini and Eniwetok. Oceanographic work carried on by the Scripps Institution and the Navy Electronics Laboratory has also shown evidence of subsidence on a comparable scale over vast areas in the central Pacific. The Mid-Pacific Mountains, for example, a range that is similar in size and gross morphology to the Hawaiian chain, has subsided some 4000 ft since the Cretaceous (HAMILTON, 1956, pp. 43-48; 1957, p. 5). The isostatic subsidence of individual volcanoes as postulated long ago by MOLENGRAFF may be, locally, a controlling factor but regional changes of level over large parts of the Pacific basin are indicated. These changes may be due to isostasy or crustal movements of other sorts, redistribution of ocean waters caused by shifting of the poles or to a combination of these and perhaps other causes. The Pacific Basin that is bounded by the Andesite Line shows evidence of submergence that contrasts with evidence of elevation beyond that line (summarized by EMERY *et al*, 1954, pp. 152-154). The widespread submergence of the basin does not appear to have been uniform and almost certainly was not continuous. Our note did not mention all possibilities or combinations of them because we were concerned primarily with evidence of emergence that interruped prolonged subsidence.

It is difficult to estimate the amount and the duration of the indicated older periods of emergence. We feel that several hundreds of feet were probably involved – more, in any event, than " small eustatic movements." The emergent periods last long enough to permit the development of a dense tropical deciduous forest and the establishment of land snails of the high island type. Additional data supporting the postulated periods of emergence and the ways in which emergent atolls could have aided in the distribution of life in the Pacific are discussed in a paper by LADD scheduled for publication in the January 1958 number of the *Journal of Paleontology*.

U.S. Geological Survey,* H. S. LADD and J. I. TRACEY, JR.
Washington 25, *D.C.*

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EMERY K. O., TRACEY J. I., JR. and LADD H. S. (1954) Geology of Bikini and nearby Atolls *U.S. Geol. Surv. Prof. Paper* 260-A, 265.

HAMILTON E. L. (1956) Sunken Islands of the Mid-Pacific Mountains,. *Geol. Soc. Amer. Mem.* 64, 97.

HAMILTON E. L. (1957) Research in marine geology at NEL. *Research Reviews*. Dept. of Navy, Washington, 1-8, July.

*(Publication authorized by the Director, U.S. Geological Survey).

The abyssal circulation

(*Received* 18 *February*, 1958)

IN my survey of the theories of ocean currents (*Deep-Sea Res.*, 1957, **4**, 149-184) several schematic interpretations of ocean circulatory patterns are presented. In this letter I wish to show how, using the same principles, it is possible to sketch in broad outline the flow pattern for the abyssal circulation of the world ocean.

It seems likely that the low temperature of deep waters in the world ocean is maintained in the face of downward diffusion of heat from the warm surface layers by a very slow upward component of velocity in the deep water. An adequate theory of the thermocline would, presumably, deduce this upward velocity as a function of surface heating, turbulence parameters, etc. We might regard the thermocline as a " pumping mechanism " which slowly draws up deep water and hence actually determines the rate of flow of the abyssal circulation. An estimate of the maximum upward component of velocity under the thermocline, w_{max}, is given in terms of the depth of the thermocline, z_t, by the equation.

$$w_{max} = \frac{\sqrt{2}}{4} \frac{\beta g \alpha l}{f^2} z_l^2 \theta_0.$$

This equation is obtained from a very primitive model* of convection on a beta-plane and contains neither the turbulence parameter nor the artificial basic stability explicity. Both enter implicitly, of course, through the very structure of the model ; both are basically objectionable, are introduced to circumvent our lack of physical knowledge about turbulence and our inability to handle the non-linearity of the energy equation respectively. Consequently our conclusions are limited, at best, to order of magnitude considerations. If we take as representative oceanic averages

$$\beta = 2 \times 10^{-13} \text{ cm}^{-1} \text{ sec}^{-1}$$

$$g = 10^3 \text{ cm sec}^{-2}$$

$$\alpha = 2 \times 10^{-4} \text{ °C}^{-1}$$

$$\theta_0 = 10 \text{°C}$$

$$f = 10^{-4} \text{ sec}^{-1}$$

$$l = 5 \times 10^{-9} \text{ cm}^{-1}$$

$$z_l = 2{\cdot}10^4 \text{ cm}$$

we find that w_{max} is of the order of 3×10^{-5} cm sec^{-1}. Since the area of the ocean at 2000 m is about 3×10^{14} m^2, the total upward flux of water across the 2,000 m level over the entire world ocean is

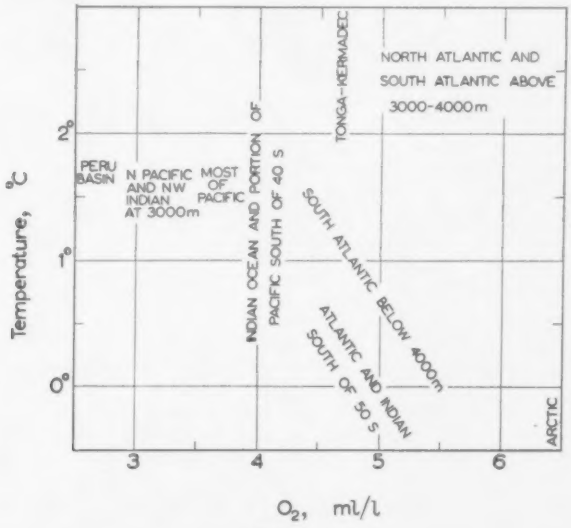

Fig. 1.

of the order 90×10^6 m^3 sec^{-1}, about twice the maximum estimated by analysis of hydrographic data. The slow upward flow over most of the ocean must be compensated for somewhere by downward flowing sources of deep water. I envisage these deep-water sources as occurring in very limited areas of weak gravitational stability where the thermocline " springs a leak." The location of these sources is apparently very sensitive to climatic factors ; we determine it by consideration of the distribution of dissolved oxygen in the ocean below 3,000 m (Fig. 1). Evidently the two sources are in the North Atlantic, and in the Weddell Sea (heavy black circles in Fig. 2); there is no source

*Henry Stommel and George Veronis (1957) *Tellus* **9**, 401-407, to which the reader is referred for definitions of quantities : the above relation being derived by substituting $Gz_l = 1$ into equation (20).

in the Arctic regions of the Pacific Ocean. The simple beta-plane convective model also assures us that the wind has no effect on the water below 2,000 m. Therefore, we have a distributed " sink " more or less over the entire ocean below 2,000 m acting on the water below ; and two point " sources." To complete the picture of the thermal circulation in the ocean we must connect the distributed sink to the sources in a way consistent with the dynamics of the fluid on a beta-plane or rotating sphere.

The streamlines in Fig. 2 are sketched following the modified form of Goldsbrough's method for the rotating sphere as described in my survey article. Because of the distributed " sink " the

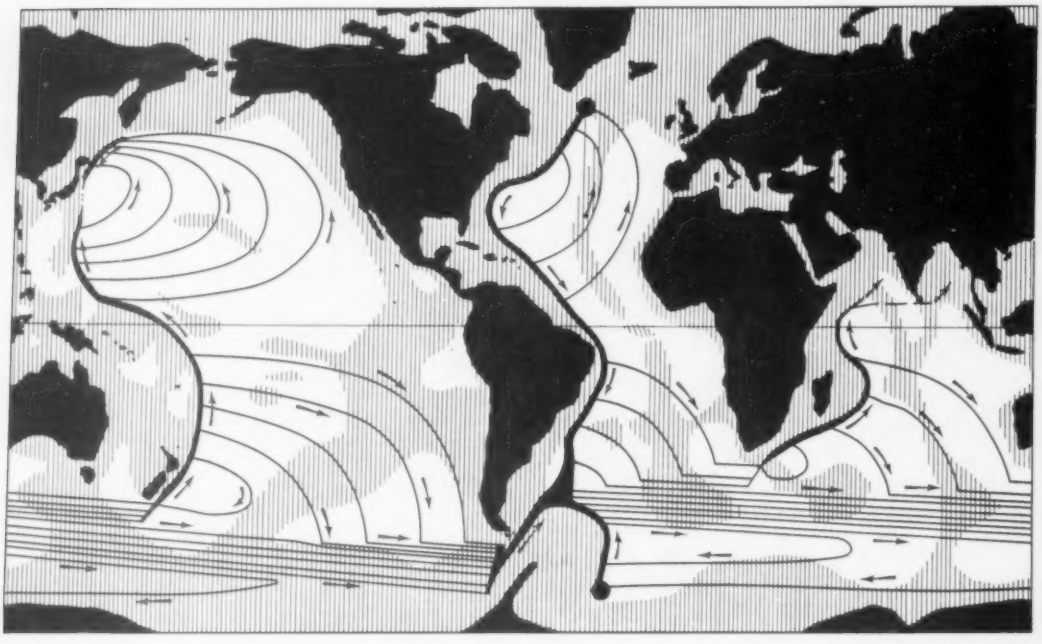

Fig. 2.

flow below 2,000 m is everywhere horizontally convergent, hence the meridional component of velocity below 2,000 m must everywhere in the interior of the ocean be directed away from the equator ($\beta v = -f \operatorname{div}_h \vec{v}$): except at the equator itself where it must vanish. Having fixed the meridional component and vertical component, the zonal component is determined by the continuity equation working westward from the eastern coasts. At the western coasts intense boundary currents are introduced as necessary to connect with the sources. The chief ambiguity is how much water to admit through Drake Passage ; the Antarctic Circumpolar Current Transport is fixed however. Summarizing the features of flow deduced in Fig. 2 : If the two sources each have strength 20 ($\times 10^6$ m^3/sec), then the western boundary currents are : western North Atlantic, 24 southward ; western South Indian, 14 northward ; western South Pacific, 30 northward ; western North Pacific, less than 10, directed toward 30 N. latitude circle. The zonal transport of the Antarctic Circumpolar Current (below 2,000 m) is 50 across 55 S. latitude circle. In the interior of all oceans at mid-latitudes below 2,000 m the mean meridional component of velocity is of the order of 0·03 cm sec^{-1}. The value of w_{max} is $1{\cdot}5 \times 10^{-5}$ cm sec^{-1}.

The above presentation is in the nature of a *tour-de-force*. One cannot pretend that it describes the the abyssal circulation accurately in detail.

Woods Hole, Mass., U.S.A. HENRY STOMMEL

Contribution No. 953 from The Woods Hole Oceanographic Institution.

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OBITUARY

Carl-Gustaf Arvid Rossby (1898–1957)

PROF. CARL-GUSTAF ARVID ROSSBY, Director of the Institute of Meteorology of the University of Stockholm and Research Associate of the Woods Hole Oceanographic Institution, died suddenly on 19 August, 1957 in Stockholm at the age of 58.

Born in Stockholm 28 December, 1898, ROSSBY was educated in Sweden, receiving his "Kandidat" in theoretical mechanics in 1918. He joined the group of young men studying under Dr. V. BJERKNES at the Geophysical Institute in Bergen and there became fired with enthusiasm for the discoveries in oceanic and atmospheric circulations, including the air-mass and polar front theories developed by the group. In Bergen he met or worked with such figures as B. HELLAND-HANSEN, H. U. SVERDRUP, the young J. BJERKNES, H. SOLBERG and T. BERGERON. Under the stimulus of these associations ROSSBY's career in meteorology and his interest in oceanography began to dominate his entire life and thought. When V. BJERKNES went for a year to the University of Leipzig, the young meteorologists, including ROSSBY, followed him. Through work at the Aeronautisches Observatorium in Lindenberg, near Berlin, in that year (1921) ROSSBY became familiar with the upper air and with problems of the flow of air in the turbulent-exchange layer.

In 1922 he returned to Stockholm to settle in the routine of duties in the Swedish Meteorologic Hydrologic Service. Although he was recognized as an outstanding young meteorologist by the officials of that organization, he seemed to be straining for greater freedom of thought and action. During this time he accompanied the S.S. *Conrad Holmboe* expedition to Jan Mayen and eastern Greenland in the summer of 1923, assisting in the meteorological and oceanographic work ; *H.M.S. af Chapman* around the British Isles in the summer of 1924 as meteorologist and the same vessel in a cruise to Portugal and Madeira in the summer of 1925 as meteorologist. Meanwhile he studied mathematical physics at the University of Stockholm and received his " Licentiat " in 1925.

ROSSBY then applied for and received a fellowship of the American-Scandinavian Foundation and in 1926 he arrived in the United States to start his research at the only meteorological centre existing in the United States at that time — the Government Weather Bureau in Washington. Although thwarted by an uninspired bureaucracy, the eager young Swede seemed to break into a run as a research scientist and during the two years 1925–1927 he published his first really significant papers — a series of six of them, all of top quality. Atmospheric turbulence was the subject of three of them, bringing simple clarity to a previously confused subject. Two papers on the dynamics of an air column extending through the stratosphere showed such a deep insight into the problem of pressure changes in the atmosphere that they put to rest a fallacious " paradox " that had troubled the greatest minds in meteorology.

In 1926 the newly organized Daniel Guggenheim Fund for the Promotion of Aeronautics sent representatives to the Weather Bureau looking for a young man with energy and a skyward outlook to work on meteorological problems of the developing air age. In CARL ROSSBY they found the man they were looking for, and presently he was laying the plans for the type of weather service that would be needed to serve the airways of the world. In 1927 and 1928 he organized the first airway meteorological service on an experimental basis in California, which became the pattern for the present system. In 1928 he was called to the task of organizing the first university-grade programme of meteorological instruction in the United States at the Massachusetts Institute of Technology. The Daniel Guggenheim Fund for the Promotion of Aeronautics had established the course and ROSSBY was given the rank of associate professor ; but before long he had his full professorship.

At M.I.T. ROSSBY exercised that art of leadership for which he was world famous. His students and associates almost worshipped him ; they reveled in the stimulating discussions they had with him and strove to heights of accomplishment that would not have been possible under any ordinary

man. They were participating in a crusade, aimed at modernizing meteorology and bringing the benefits of the "Norwegian School" or, subsequently, of the "Rossby School" to American meteorology.

In his research during the eleven years while he was at M.I.T., ROSSBY attracted world-wide attention with his contributions to the thermodynamics of air masses, his application of the results of VON KÁRMÁN, PRANDTL and others to turbulence in the atmosphere and in the oceans, his studies of lateral mixing and interaction of the ocean-atmosphere boundary layer. Then, through a study of motions on isentropic surfaces in the atmosphere be began to turn his attention to large-scale motions which, in turn, led to investigations of the general circulation of the atmosphere. Toward the end of his M.I.T. period he re-examined theories of the general circulation and began to apply vorticity and momentum concepts which have had a profound influence on the thinking of meteorologists to the present day.

In 1939 ROSSBY left M.I.T. to become the assistant chief for research in the U.S. Weather Bureau. Despite heavy administrative responsibilities he continued to work on the problems of the large-scale motions and submitted for publication papers developing the theory for the displacement of the long waves in the atmosphere, sometimes called the "Rossby waves." This work was continued in his new post, that of chariman of the Department of Meteorology, created in 1940, at the University of Chicago. In these ideas, ROSSBY was always aware of their application to oceanography ; in fact, some of the important contributions were published in *Journal of Marine Research.*

During World War II ROSSBY, from his position at the University of Chicago and almost world-wide travels, played a leading role in organizing the training of military meteorologists and the application of modern concepts to problems of the atmosphere which were of importance in the war. During this busy period he found time for research and was able to perfect his ideas on the long waves of the atmosphere.

In the post-war period he gathered around him an outstanding group of young men at the University of Chicago. The discovery of the jet stream was largely due to ROSSBY. At the same time he worked with Dr. JOHN VON NEUMANN and Dr. JULE CHARNEY in the development of equations for prediction of the upper-air flow by high-speed electronic computers. The scheme used in numerical prediction today is largely derived from equations and relationships originally developed by ROSSBY.

In 1947 the native Swede, although a citizen of the United States since 1938, began the interest which finally returned him to his native land. The Swedish government needed his help in organizing improved meteorological education and services in that country. An Institute of Meteorology was started at the University of Stockholm with ROSSBY as director, and he began to divide his time between Stockholm and the University of Chicago. For personal reasons and for the convenience of U.S. Navy support of his work, his American connexions were transferred to the Woods Hole Oceanographic Institution in 1952-53, and this arrangement was in force at the time of his death.

His principal activities in Stockholm centered around the development of numerical prediction systems for European weather, in which he met with remarkable success. He founded the geophysical journal *Tellus* which became an international force in geophysics, especially meteorology, and he gained recognition of the Stockholm Institute by various international bodies as officially an international institute. It was indeed an international institute, with students and associates from many lands. Here the same inspiring leadership of young scientists that characterized his work at M.I.T. and Chicago was again in evidence.

Beginning in 1954 ROSSBY devoted his attention to an entirely different field of meteorology and oceanography — a form of geochemistry. This interest began with a study of the chemical composition of rain water but broadened to include all aspects of the chemical balance of the oceans and the atmosphere. He also interested himself in the deep circulation of the ocean. These were the unfinished interests at the time of his death.

On the personal side of his life, it should be stated that he married HARRIET ALEXANDER of Boston after his first year at M.I.T. and that they had three children, the eldest, a son, STIG ARVID, now married and living in Chicago. Mrs. ROSSBY and the other two children are living in Stockholm.

HORACE R. BYERS

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NEWS AND NOTES

National Academy of Sciences National Research Council

Committee on Oceanography

THE National Academy of Sciences – National Research Council has formed a Committee on Oceanography to promote the future development of oceanography in the United States. The Committee is sponsored by the Office of Naval Research the Atomic Energy Commission and the Fish & Wildlife Service.

Harrison Brown of the California Institute of Technology, is Chairman, and the members are : Maurice Ewing, Lamont Geological Observatory; Columbus Iselin, Woods Hole Oceanographic Institution; Fritz Koczy, Marine Laboratory, University of Miami ; Sumner Pike, former Commissioner of the Atomic Energy Commission ; Colin Pittendrigh, Princeton University ; Roger Revelle, Scripps Institution of Oceanography ; Gordon Riley, Bingham Oceanographic Laboratory, Yale University ; Milner Schaefer, Inter-American Tropical Tuna Commission; and Athelstan Spilhaus, Minnesota Institute of Technology.

The Committee held its first meeting on November 23 1957, in New York City and subsequent meetings have been held in Washington D.C., La Jolla, and Miami.

Six panels have been formed to examine particular areas :

(1) Panel on New Research Ships, Columbus Iselin, Chairman

(2) Panel on New Devices for Exploring the Ocean, Allyn Vine, Chairman

(3) Panel on Radioactive Waste Disposal at Sea, Roger Revelle, Chairman

(4) Panel on International Co-operation in the Marine Sciences, Athelstan Spilhaus, Chairman

(5) Panel on Ocean Resources, Robert Snider, Chairman

(6) Panel on Basic Research in the Marine Sciences, Alfred Redfield, Chairman.

The Committee is attempting, with the assistance of the panels, to : (i) formulate recommendations concerning our long-range national policy in oceanography, (ii) to assist in all possible ways in increasing both the quantity and quality of basic research in the marine sciences and (iii) to advise specific government agencies concerning problems which involve the marine sciences.

Washington, D.C., U.S.A.
7 April 1958.

RICHARD C. VETTER,
Executive Secretary.

International Oceanographic Congress

THE American Association for the Advancement of Science in co-operation with UNESCO and the SPECIAL COMMITTEE ON OCEANIC RESEARCH of ICSU is planning and organizing an International Oceanographic Congress to be held during a two-week period from 30 August to 12 September 1959 at The United Nation's Building, New York.

The purpose of the Congress is to provide a common meeting ground for all sciences concerned with the oceans and the organisms contained in them. The Congress will be devoted to the fundamentals of the marine sciences rather than to their applications.

It has been agreed by the organizing committee that the Congress will be centred around five symposia on the oceans :

1. The history
2. The boundaries
3. The deep sea
4. Dynamics of organic and inorganic substances
5. The marine life regime.

1. *The history*—Includes discussions of the shape and structure of the ocean basins, the acting forces and processes, the origin of sea-water and marine organisms, the stratigraphy of the deep-sea and the climatic record.

2. *The boundaries*—Includes discussions of the coupling of sea and air, sea level, epicontinental sediments, estuarine and nearshore circulation (including the estuarine environment), influence of land masses on the behaviour and distribution of marine organisms, and surface films and their importance in exchange processes.

3. *The deep sea*—Includes discussions of the geo-chemistry and physics of circulation, stirring and mixing in the ocean, nature and origin of bathypelagic life, distribution of pelagic sediment types (biological and physical interpretations), nuclear processes in pelagic sediments and special characteristics of abyssal organisms.

4. *Dynamics of organic and inorganic substances*—Includes discussions of physical chemistry of sea-water, biologically active substances in sea-water, primary production, balance between living and dead organic matter in the oceans, exchanges between sea and air, exchanges between sediments and sea-water and vertical transport in the ocean.

5. *The marine life regime*—Includes discussions of the paleogeography of marine floras and faunas, biogeographical regions in the sea, evolution and adaptation in the sea, the behaviour of marine organisms as influenced by environmental factors, physiology of marine plants, and the culture of marine organisms as a means of understanding environmental influence on populations.

Each topic for a symposium will be considered for two consecutive days. Three invited lectures will be given each morning. The afternoon sessions will be organized around the morning topics either in round-table discussions, in seminars, or in a series of papers. Several groups may run concurrently. Papers for the afternoon sessions will be selected from those received in response to this and subsequent announcements. Not all papers which have been accepted will actually be presented, but all accepted papers will be available at the meeting in mimeographed form. Titles and abstracts should be submitted as soon as possible and in no case later than 1 February 1959. The completed papers must be submitted by 1 May 1959 in order to allow time for duplication and distribution to the participants in the afternoon meetings well in advance of the meeting. All papers must have an abstract in a second language of the Congress. Papers may be presented in English, French, German, Russian, or Spanish. Simultaneous translations will be available for at least some of these languages.

The organizing committee expects that contemporary advances in the marine sciences, rather than reviews of older published work, will be presented under these broad topics. It is hoped that the younger staff members of the various oceanographic laboratories around the world will be encouraged to attend and to take part in the Congress. In order to assist with their attendance, the committee hopes to obtain funds to help defray the travel expenses of these younger participants. The committee also hope to be able to contribute towards the travel expenses of the invited speakers at the morning sessions.

This notice should be considered as preliminary. Until further notices are issued, titles and abstracts of papers, which are publicly solicited by this notice, and any other correspondence should be sent to :

Dr. MARY SEARS, Chairman,
Woods Hole Oceanographic Institution,
Woods Hole, Massachusetts, U.S.A.

Other members of the Committee on Arrangements for the Congress are : GUSTAF ARRHENIUS, JOHN CUSHING, HENRY M. STOMMEL, FRITZ KOCZY, GEORGE S. MYERS, ROGER REVELLE, GORDON LILL, LIONEL A. WALFORD and DAEL WOLFLE (ex-officio).

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BOOK REVIEW

Treatise on Marine Ecology and Paleoecology, Vol. 2, **Paleoecology**. Geological Society of America, Memoir 67, 1957. xii + 1077 pp. $10.

SOME 70 specialists have co-operated with the 19 members of a Committee of the Division of Earth Sciences, National Research Council, National Academy of Sciences, to produce this imposing volume (Volume I, on Marine Ecology, has yet to appear). The committee is to be congratulated on this result of 17 years organization and work. Six preliminary chapters examine the nature and development of the subject, and include stimulating essays on the origin of life and on organic substances that are associated with fossils. The succeeding seventeen chapters are individual essays – " selected analyses " – accounts of the paleoecology of particular units in the stratigraphical column, ranging from Pre-Cambrian to Recent. An essay on the future of marine paleoecology completes this section. Each of the chapters mentioned has references, and the last third of the volume is devoted to an annotated bibliography of marine paleoecology, arranged by plant and animal groups. Each of these bibliographies has an introductory essay, and certain of these are of considerable length and originality. The volume appears to be well indexed.

This work is not a treatise in the sense that it is not a cohesive summary of existing knowledge nor a statement of principles. It is rather an attempt to bring together under various headings observations that have been made on the habits of ancient organisms, and to show by example how paleoecology may be studied. It does a great service in revealing our ignorance and pointing out lines of investigation. Oceanographers and other students may see how geologists go about trying to reconstruct past events, almost exclusively in the shallow seas. Valuable to biologists is the survey, with references, of views on modes of life of marine fossil animals and plants.

H. B. WHITTINGTON.

PAPERS TO BE PUBLISHED IN FUTURE ISSUES

B. G. BOGOROV : Biogeographical regions of the plankton of the northwestern Pacific Ocean and their influence on the deep sea.

J. D. COCHRANE : The frequency distribution of water characteristics in the Pacific Ocean.

M. J. POLLAK : Frequency distribution of potential temperatures and salinities in the Indian Ocean.

R. B. MONTGOMERY : Water characteristics of Atlantic Ocean and of world ocean.

J. S. CREAGER : A canyon-like feature in the Bay of Campeche.

D. ROCHFORD : Total phosphorus as a means of identifying East Australian water masses.

N. G. JERLOV : Maxima in the vertical distribution of particles in the sea.

G. S. RITCHIE : Sounding profiles between Fiji, Christmas and Tahiti Islands.

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Total phosphorus as a means of identifying East Australian water masses

D. ROCHFORD

(*Received* 17 *February* 1958)

Abstract—In this paper the degree of conservatism of total phosphorus in relation to water mass composition of East Australian waters was examined.

In oceanic waters down to about 1000 m it was found that total phosphorus was generally conservative within limits of about $\pm$ 2·5 μg/l. However, some of this variability could be due to errors in water mass identification and the degree of conservatism was probably better than these limits indicate.

In the slope and coastal waters of East Australia non-conservatism is general, with positive anomalies most frequent. It is suggested that these positive anomalies in coastal, slope, and oceanic waters were caused by the elevation and transport of phosphate rich bottom sediments. The probable factors involved in this phenomenon are discussed.

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I. INTRODUCTION

PRIOR to World War II very little was known of the concentration of total phosphorus in sea-water except from the investigation of KALLE (1935) and REDFIELD *et al.* (1957) on the proportion of organic phosphorus in the total phosphorus of certain shallow seas. ARMSTRONG and HARVEY (1950) suggested that total phosphorus could be used as a conservative property for the identification of water masses in the English Channel. COOPER (1951) working in the Celtic Sea concluded that total phosphorus in the bottom waters around the Labadie Bank was increased by vertical transport of bottom sediments. In 1953 BUSH *et al.* (1955, p. vii) examined the conservation of total phosphorus in the southern Labrador Sea, and concluded " that the concentration of total phosphorus is roughly characteristic of water masses though of doubtful utility as a tracer of water masses." In 1955 KETCHUM *et al.* demonstrated that total phosphorus determinations could be made at sea using the autoclaving technique of HARVEY (1948) and published data on the total phosphorus content of the equatorial waters of the Atlantic Ocean.

Since 1942 this Laboratory has been determining the total phosphorus content of East Australian coastal waters. Recently these determinations have also been made on the oceanic waters of the Tasman and Coral Seas. Because it is hoped to use total phosphorus as an identifying property of water masses in these seas, it was felt desirable to examine its degree of conservatism from data up to 1955 before a greatly increased programme of analysis for this property was developed.

II. MATERIAL AND METHODS

The data used in this paper are available in the Oceanographical Station Lists of the Division of Fisheries and Oceanography (C.S.I.R.O. 1956, C.S.I.R.O. 1957). The analytical methods used in total phosphorus determination have been published (ROCHFORD, 1951). The separation of the soluble and particulate fractions of the total phosphorus was made by centrifugation for 10 min at 12,800 g.

The various constituents of total phosphorus were separated as follows :—

(a) Inorganic phosphorus content of original sample.

(b) Total phosphorus content of original sample.

(c) Total phosphorus content of supernatant after centrifugation.

The soluble organic phosphorus was calculated as the difference between (c) and (a). The particulate phosphorus was calculated as the difference between (b) and (c).

Centrifugation rather than filtration (REDFIELD *et al.* 1937) was used because it allowed rapid handling of large numbers of samples.

Using a suspension of kaolin in distilled water (100 mg/l.) the efficiency of separation by this method varied from 87 to 98 per cent with an average of 93 per cent for six determinations. Because the particulate matter occurring under natural conditions in sea-water would have different particle sizes and specific gravities from those of kaolin, it is impossible to generalize from these results. It is considered likely, however, that the greater part of mineral sediments would be so separated.

Since however some of the detrital and living organic matter of less specific gravity than the mineral sediment would not be separated by centrifugation the particulate phosphorus values in this paper must be considered minimal estimates and somewhat arbitrary in nature.

III. THE TOTAL PHOSPHORUS COMPOSITION OF EAST AUSTRALIAN COASTAL AND SLOPE WATERS

(*a*) *The Particulate Phosphorus Content of Pt. Hacking Waters*

Off Pt. Hacking two stations were worked on the continental shelf. One in position latitude 34° 05′ 30″S longitude 151° 15′ 30″E some five miles offshore was sampled to 100 m. This is referred to as the Pt. Hacking shelf station. The other was in position latitude 34° 05′S longitude 151° 13′E, some three miles offshore It is called the Pt. Hacking coastal station in this paper.

At both of these stations at least 15 m of water separated the deepest sample from the sea bottom. It is not considered likely therefore that accidental contamination of the sea-water samples by agitation of the bottom sediments could have occurred. Any introduction of sediment into the sea-water samples must have been caused by natural turbulence, capable of elevating bottom sediments to heights of at least 15 m off the sea bed.

During 1951-56 a total of 208 surface samples were collected at the Pt. Hacking coastal station. Of these 96 or 46 per cent had no particulate phosphorus separable by the centrifuge method. Fig. 1 (a) shows that, of the remaining 54 per cent, a high proportion contained particulate phosphorus between 5 and 35 per cent relative to total phosphorus; with some indication of a modal value around 20-25 per cent.

At 50 m for the same station and period, 191 samples were collected; of these 92 or 48 per cent had no detectable particulate phosphorus. Of the remaining 52 per cent the highest proportion contained between 5 and 20 per cent particulate relative to total phosphorus, with a modal value not clearly defined. (Fig. 1b).

During the period 1953-56, 120 surface samples from the shelf station were analysed for particulate phosphorus content. Of these 47 or 39 per cent contained no detactable particulate phosphorus. Fig. 1 (c) shows that for the remaining 61 per cent the majority of samples contained between 5 and 25 per cent particulate relative to total phosphorus with a modal value around 10-15 per cent.

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At 50 m for the same station and period, 122 samples were analyzed. Of these 55 per cent contained no detectable particulate phosphorus. Of the remainder (45 per cent) the majority contained (Fig. 1d) between 5 and 20 per cent particulate relative to total phosphorus, with a modal value in this range.

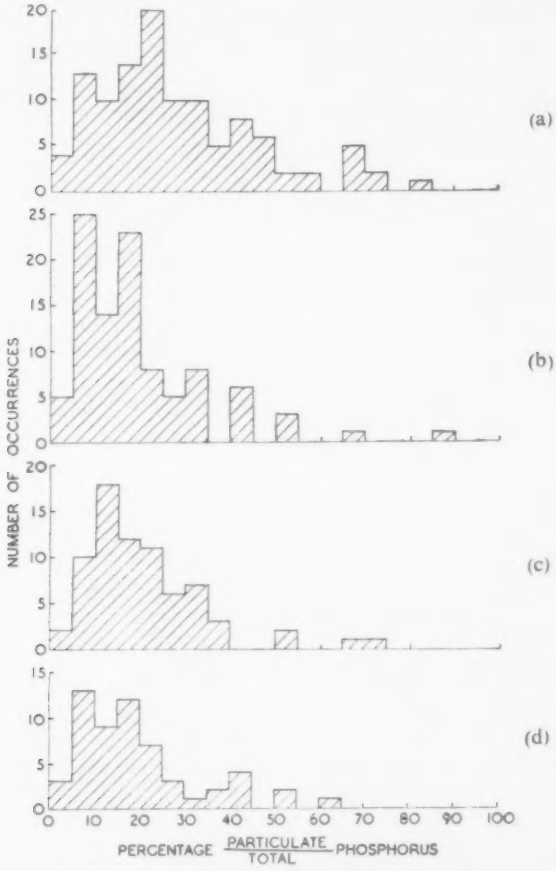

Fig. 1. The frequency distribution of the percentage ratio of particulate to total phosphorus.
(a) Pt. Hacking coastal station 0 m.
(b) Pt. Hacking coastal station 50 m.
(c) Pt. Hacking shelf station 0 m.
(d) Pt. Hacking shelf station 50 m.

REDFIELD *et al.* (1937) found between 4 and 18 per cent, average 10 per cent, particulate relative to total phosphorus (Table VI) in Gulf of Maine waters with an average depth of 250 m. These data were too limited to determine a modal value of the particulate to total phosphorus ratio in Gulf of Maine waters. However, it probably lies between 4 and 18 per cent. In view of the minimal nature of the method of separation of particulate phosphorus in Port Hacking waters (Section II) it must be concluded that these waters have a higher relative particulate content. This either indicates a very much higher biological productivity of organic particulate phosphorus in Pt. Hacking than in Gulf of Maine waters, or, as is considered more

likely, a much higher proportion of mineral sediments containing phosphates in the former.

(b) Total Phosphorus Changes During Slope Water Movements

(1) Pt. Hacking 1954-55. ROCHFORD (1957) has shown that the East Australian current contains varying proportions of two water masses, a Coral Sea water of high chlorinity and moderate temperature and a South Equatorial water of low chlorinity and high temperature. Off the New South Wales coast the subsurface slope waters at depths of 200-400 m are composed of mixtures of the Coral Sea and the deep sub-Antarctic water masses, with little influence of the south Equatorial water mass at the surface.

During the spring and early summer period (September to December) changes occur in the bottom temperature, chlorinity and other hydrological properties of New South Wales coastal waters. These have been ascribed to onshore movements of adjoining slope waters lying at depths of between 200 and 400 m. This assumption is based upon the similarity of hydrological properties only and no current measurements are available to substantiate or to show its possible velocity or turbulence characteristics.

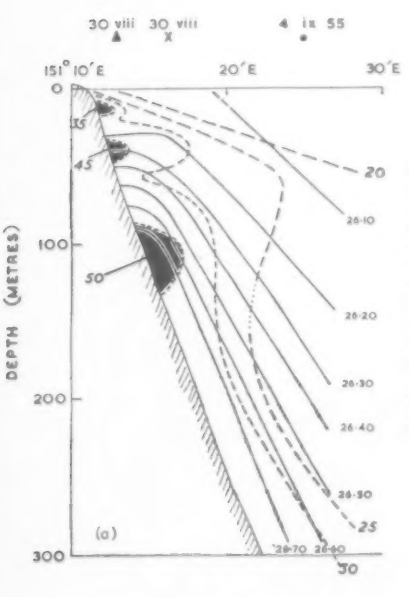

Fig. 2 (a).

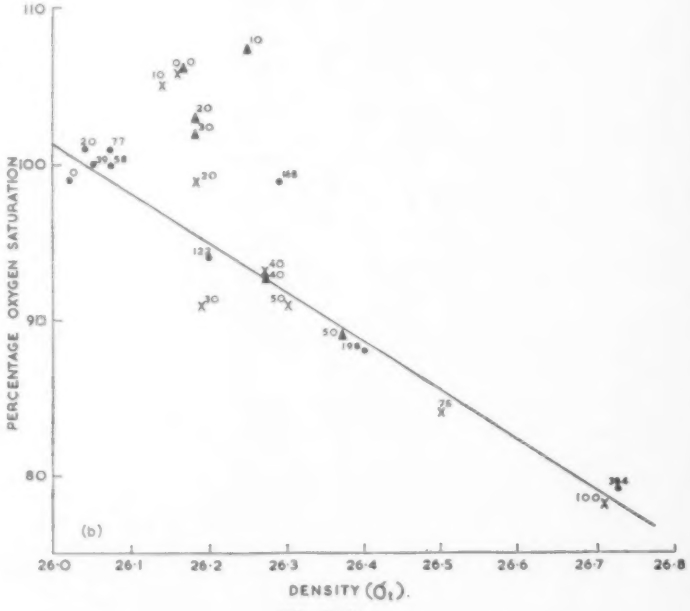

Fig. 2 (b).

Fig. 2 (a). The distribution of total phosphorus relative to density (σt) surfaces off Pt. Hacking between August 30th, and September 4th, 1955.

Fig. 2 (b). The relationship of percentage oxygen saturation to density (σt) at the stations indicated in 2 (a).

Fig. 2 (a) shows the distribution of total phosphorus in relation to isopycnic surfaces during such a slope water invasion off Pt. Hacking in late July and early August 1955. Along these isopycnic surfaces the percentage oxygen saturation remains relatively constant (Fig. 2b), except for values near the surface where supersaturation in

oxygen occurs. However, total phosphorus seems to be increasing shorewards on these isopycnic surfaces (Fig. 2a) and centres of very high total phosphorus occurred near the bottom at the two onshore stations.

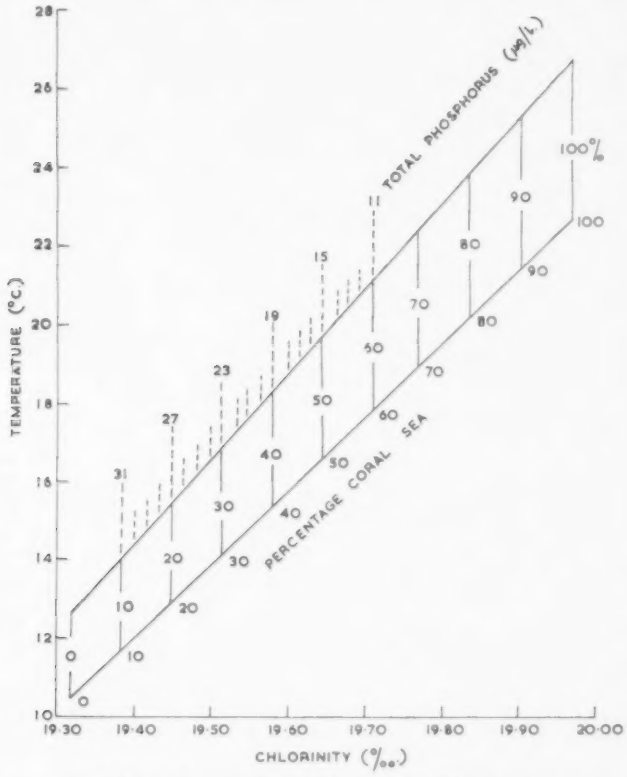

Fig. 3. The percentage of Coral Sea water mass in various chlorinity-temperature combinations of Pt. Hacking slope water. The upper scale denotes *in situ* total phosphorus values for various slope water mixture, taken from Fig. 4.

If the mixing diagram in Fig. 3 (from ROCHFORD, 1957) is used to characterize the water mass composition of samples from the 200-400 m stratum of the slope waters off Pt. Hacking in 1954-55, and the percentage values so obtained plotted against the total phosphorus content of the same samples (Fig. 4) a near linear relationship is evident. During the months September to December 1954-55 therefore total phosphorus was a conservative property within this depth stratum of these slope waters. From this slope water relationship a scale of *in situ* total phosphorus of the various slope water mixtures has been entered on Fig. 3.

Wherever a particular combination of chlorinity and temperature lying within the limits of Fig. 3 is found in coastal waters off Pt. Hacking, it is probable that an onshore movement of deep slope waters has occurred. The lowered oxygen content generally provides confirmatory evidence of subsurface origin as for example in Fig. 2 (b). From the total phosphorus scale in Fig. 3, it is possible to determine the original *in situ* value of this property for the particular chlorinity-temperature com-

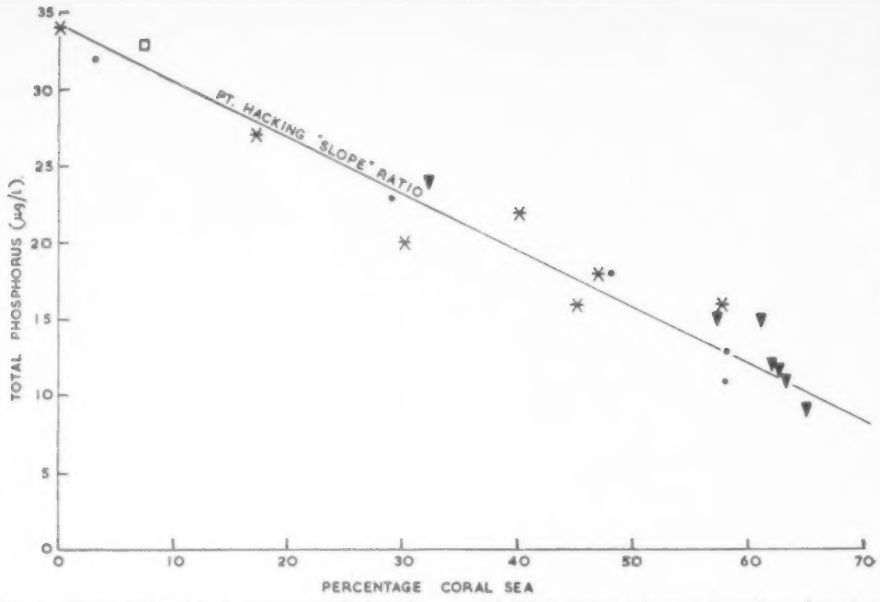

Fig. 4. The relationship between total phosphorus and slope water mixtures (previous figure) off Pt. Hacking during December 1954 to November 1955.

■ . . . . . April data
+ . . . . . May data
● . . . . . August data
□ . . . . . September data
▼ . . . . . November data
✱ . . . . . December data

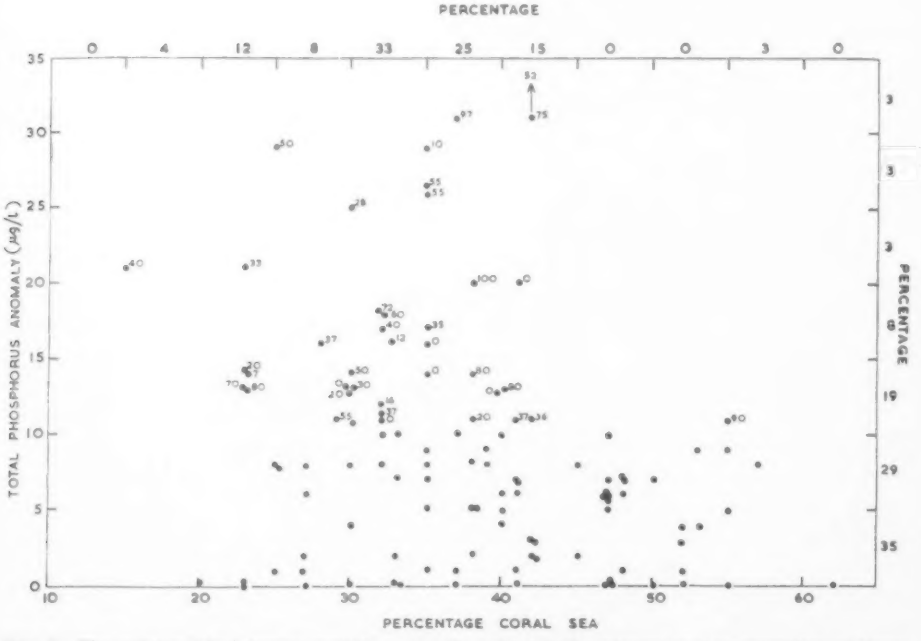

Fig. 5. The relationship between positive anomalies of total phosphorus and composition of slope waters occurring at the shelf station off Pt. Hacking during August to December 1954/55. The numbers in the body of the figure refer to the percentage particulate to total phosphorus anomaly ratio.

bination. From a comparison of the total phosphorus of the same water prior to and after its onshore movement an estimate on its conservatism in coastal regions can be gauged. In many cases the observed value in coastal waters exceeds the *in situ* value and this difference is called a positive total phosphorus anomaly. In rare cases the opposite situation is found and the difference is called a negative anomaly.

Using the 1954-1955 data from the two Pt. Hacking stations for the months September to December the magnitude of the positive total phosphorus anomalies was plotted against water mass composition of the slope waters occurring in their bottom strata. At the shelf station (Fig. 5) only 35 per cent of the 116 slope water occurrences had anomalies which were less than 5 μg/l. and were not regarded as

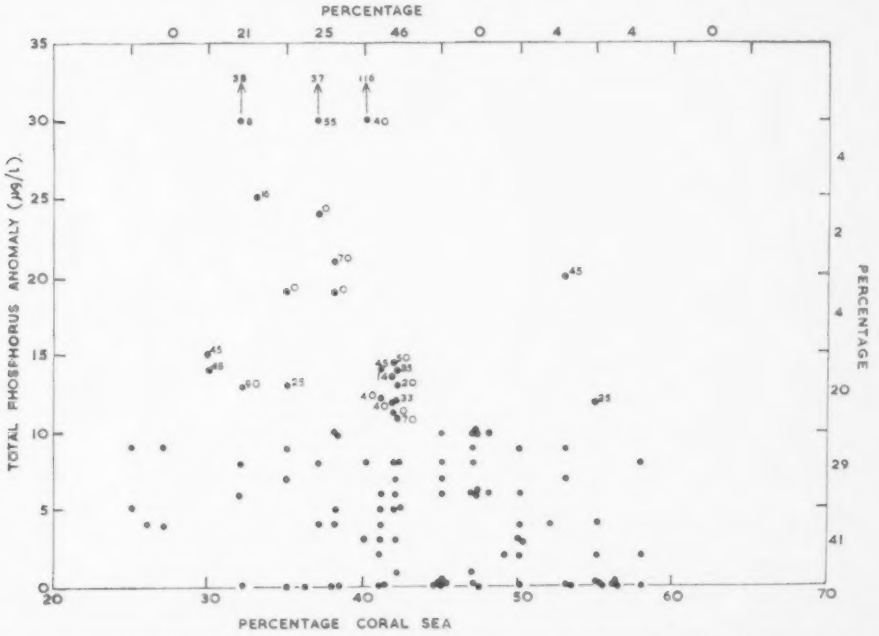
PERCENTAGE
0 21 25 46 0 4 4 0
TOTAL PHOSPHORUS ANOMALY (µg/l.)
PERCENTAGE
PERCENTAGE CORAL SEA
20 30 40 50 60 70
0 5 10 15 20 25 30 35
0 2 4 4 20 29 41

Fig. 6. A similar plotting as for the previous figure, of data at the coastal station during the same period. The numbers also refer to the same ratio as in the previous figure.

significant. Of the remaining 65 per cent, 48 had anomalies between 5 and 15 μg/l. with the remaining 17 containing anomalies as high as 52 μg/l. Of the anomalies greater than 5 μg/l., 58 per cent occurred in waters of a 30-40 per cent Coral Sea composition. Slope waters of this composition normally occur between 200 and 300 m off Pt. Hacking. Fig. 5 also shows the percentage of particulate phosphorus in the total phosphorus anomalies greater than 10 μg/l. In some cases it is evident that the particulate phosphorus could account for the greater part of the anomaly. In many cases positive anomalies can occur without any detectable particulate phosphorus. However as indicated in a previous section it is possible that inefficient separation of such particulate matter could be responsible for this lack of detection.

At the coastal station (Fig. 6) 59 per cent of the 105 slope water occurrences had total phosphorus anomalies greater than the significant level of 5 μg/l. Of these

49 per cent had anomalies between 5 and 15 μg/l. with 10 per cent greater than 15 μg/l. The maximum number of anomalies (46 per cent) greater than 10 μg/l. occurred in slope waters of 40-45 per cent Coral Sea from an *in situ* depth of 100 to 200 m. At this station the particulate phosphorus content as determined could not be considered as a consistent or significant part of the anomalies (Fig. 6).

(2) Eden 1954-55. The slope waters off Eden (latitude 37° 04′S) are also composed of varying proportions of Coral Sea and sub-Antarctic water masses. Their total phosphorus content for the months April to November of 1954-55 is conservative (Fig. 7) although to a lesser degree than the slope waters off Port Hacking (Fig. 4). It is significant that the total phosphorus content of Eden slope waters is about

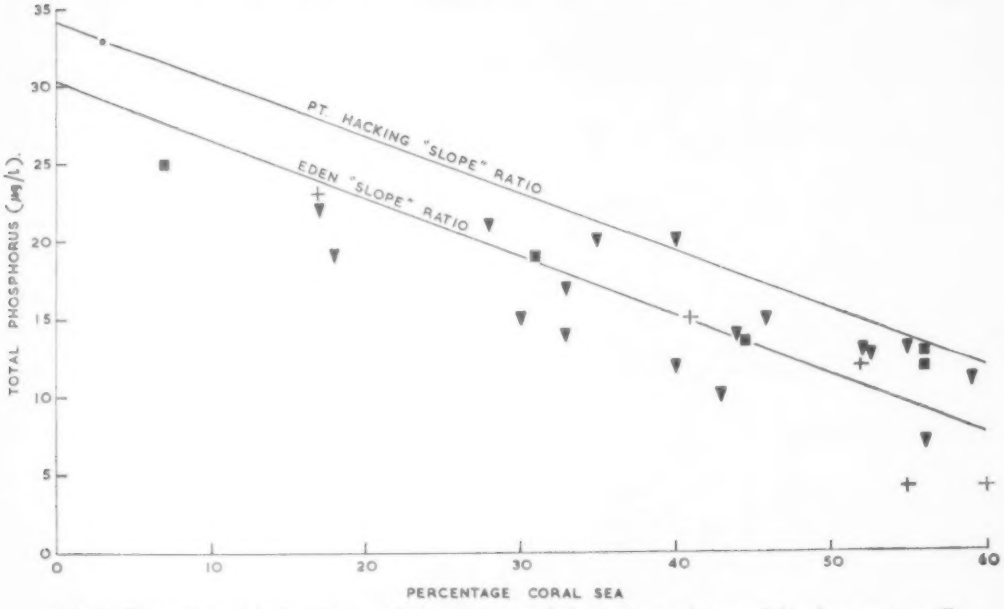

Fig. 7. The relationship between total phosphorus and slope water mixture of the slope waters off Eden. The line of the Pt. Hacking slope ratio has been entered for comparison. The symbols denote months as in Fig. 4.

4 μg/l. less than that of Pt. Hacking. This difference will be considered in relation to the total phosphorus structure of the intermediate waters of the Tasman and Coral Sea in Section IV (b).

By a process of analysis similar to that in the previous section, the magnitude and water mass relationships of the positive total phosphorus anomalies at the Eden coastal station (latitude 37° 04′S, longitude 150° 05′E) for 1954-55 were examined (Fig. 8). Because of the less frequent occurrences of slope water at the Eden station only 15 values were plotted, but of these 53 per cent had anomalies greater than the significant level of 5 μg/l.

(3) Eastern Bass Strait, April 1955. In April 1955 the waters of the eastern approaches to Bass Strait were formed by mixing between a surface water mass (i) (Cl‰ 19·73 Temp. 20·0°C) and a deep water mass (ii) (Cl‰ 19·34 Temp. 11·4°C). For the various mixtures of these two water masses in this region Fig. 9 shows that

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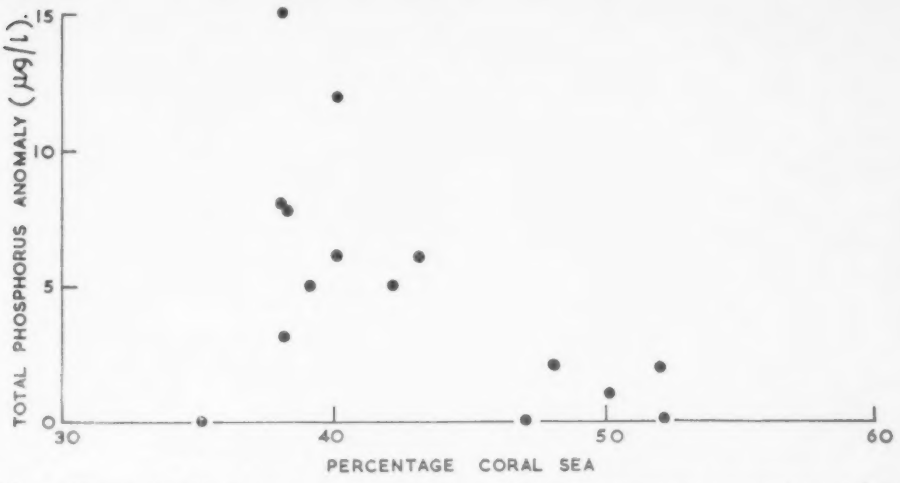

Fig. 8. The relationship between positive anomalies of total phosphorus and composition of slope waters at the Eden coastal station during May to November 1954/55.

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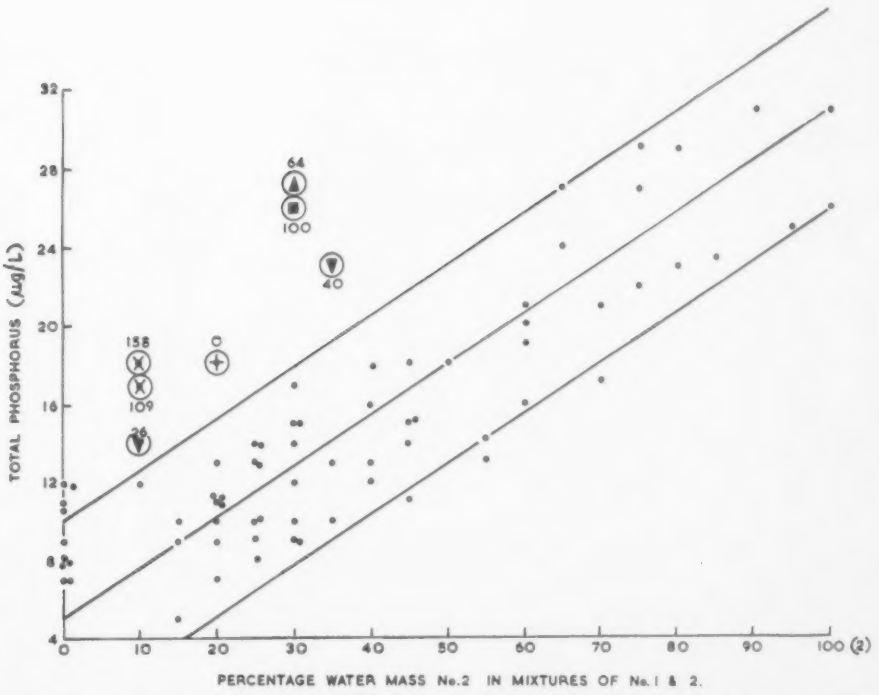

Fig. 9. The relationship between water mass composition and total phosphorus of stations in Eastern Bass Strait in April 1955. The envelopes have been drawn at the limit of a cumulative error of $\pm$ 2·5 µg/l. total phosphorus and $\pm$ 10 per cent water mass analysis. Positive anomalies outside of their limits are identified by different symbols and their depths of occurrence are also given.

within cumulative error limits of ± 10 per cent water mass composition and $\pm 2{\cdot}5\ \mu g/l.$ total phosphorus, total phosphorus was advectively controlled except for a small number of positive anomalies. These anomalies occurred at stations adjacent to the continental slope (Fig. 10) and generally at intermediate depths (Fig. 9).

In April 1955 a diversion of flow of the East Australian current into the eastern approaches of Bass Strait occurred (Fig. 10) and the gradient of positive total phosphorus anomalies is consistent with an increasing degree of turbulent stirring and transport at intermediate levels of phosphate rich bottom sediments along the shallowing path of this current.

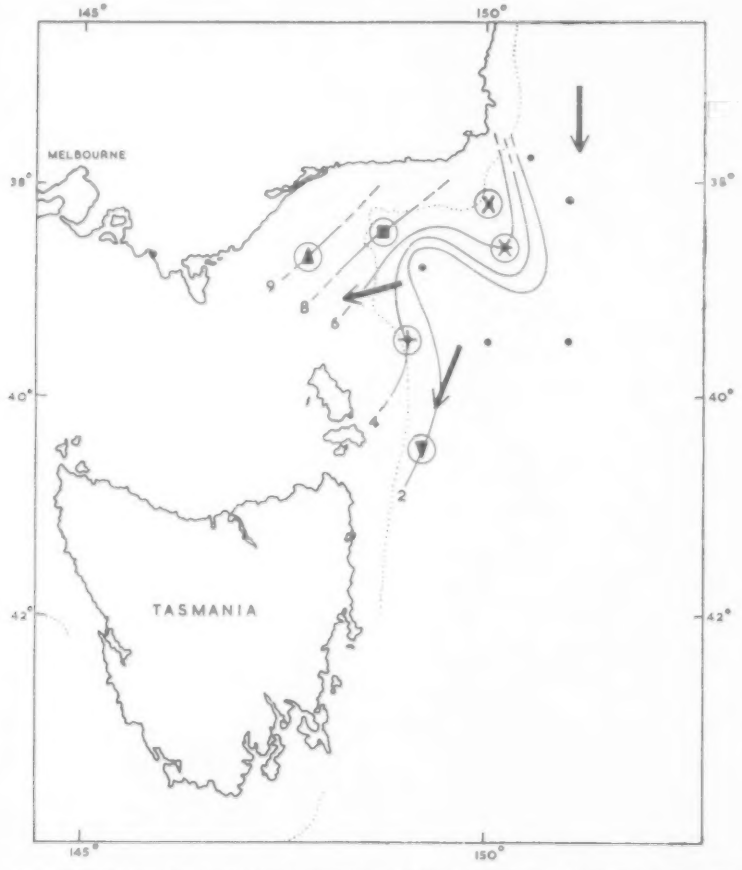

Fig. 10. The distribution of the positive anomalies of total phosphorus in Eastern Bass Strait, April 1955. Isolines showing the magnitude of this anomaly and the probable major surface currents are also shown.

IV. THE TOTAL PHOSPHORUS COMPOSITION OF EAST AUSTRALIAN OCEANIC WATERS

(*a*) *Surface Waters* 1955

In November-December 1955 the northern Tasman Sea and the eastern and western

Table 1. *Surface Regional water masses of the Tasman and Coral Seas. November-December*, 1955

Regional Water Mass No.	*Position*	*Mean Chlorinity* (‰)	*Mean Temperature* (°C)
1	N.W. Coral Sea	18·20	27·4
2	N.E. Coral Sea	19·27	28·4
3	S. Coral Sea	19·85	22·9
4	N. Tasman Sea	19·75	19·8

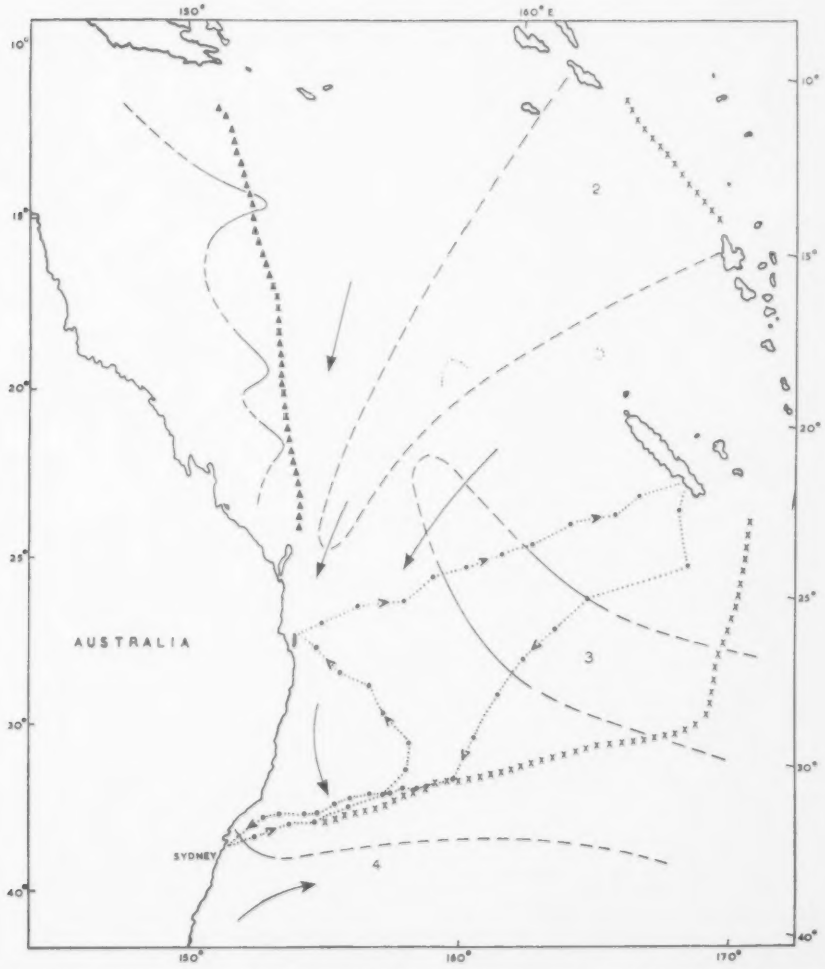

Fig. 11. The position of the stations sampled in the Tasman and Coral Seas during November-December 1955. The numbers refer to the water masses listed in Table 1, with their approximate boundaries shown. The arrows show the major movements of surface waters in the Western region.

●– – – – – ● *Derwent Hunter*
× × × × × × *Tulagi*
▲▲▲▲▲▲▲ *Malaita*

boundaries of the Coral Sea were sampled by F. R. V. *Derwent Hunter* and various merchant ships (Fig. 11).

Within this area it was possible to distinguish four surface regional water masses (Table 1) whose approximate boundaries and probable direction of movement are shown in Fig. 11. In the northern portion of this area the majority of the surface waters down to the halocline were formed by mixing between water masses (2) and (3).

Using only chlorinity-temperature combinations lying within the envelope on the mixing diagram, connecting the mean properties of water masses (2) and (3)

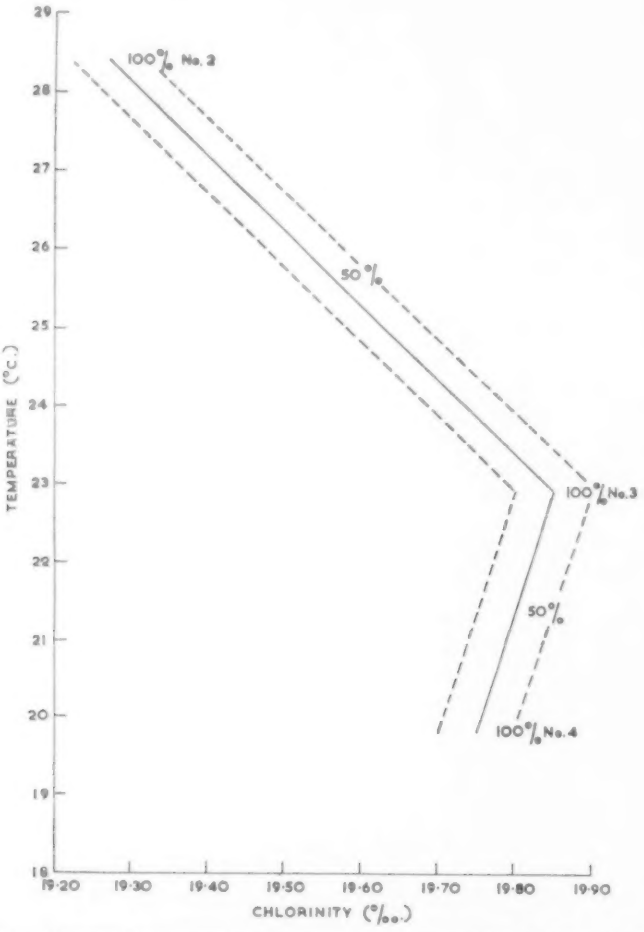

Fig. 12. A mixing diagram for computing the water mass composition of the surface waters of the Tasman and Coral Seas in November-December 1955. The dashed line has been chosen at a cumulative error limit of ± 0·5°C in temperature and ± 0·02‰ in chlorinity.

(Fig. 12) it was possible to examine the surface total phosphorus to water mass composition of these waters (Fig. 13). The 50 per cent mixture of (2) and (3) on Fig. 13 corresponds to the South Equatorial water mass off Sydney with a mean total phosphorus content in summer of 10 μg/l. (ROCHFORD, 1957). Using this

value as a guide a trend line was visually drawn to include within an error envelope of $\pm 3\ \mu g/l.$, 80 per cent of values. From this trend line mean total phosphorus values of 17 $\mu g/l.$ and 15 $\mu g/l.$ for water masses (2) and (3) respectively were found.

In the southern portion of the area sampled in November-December 1955 (Fig. 11) the majority of the surface waters down to the halocline were composed of mixtures

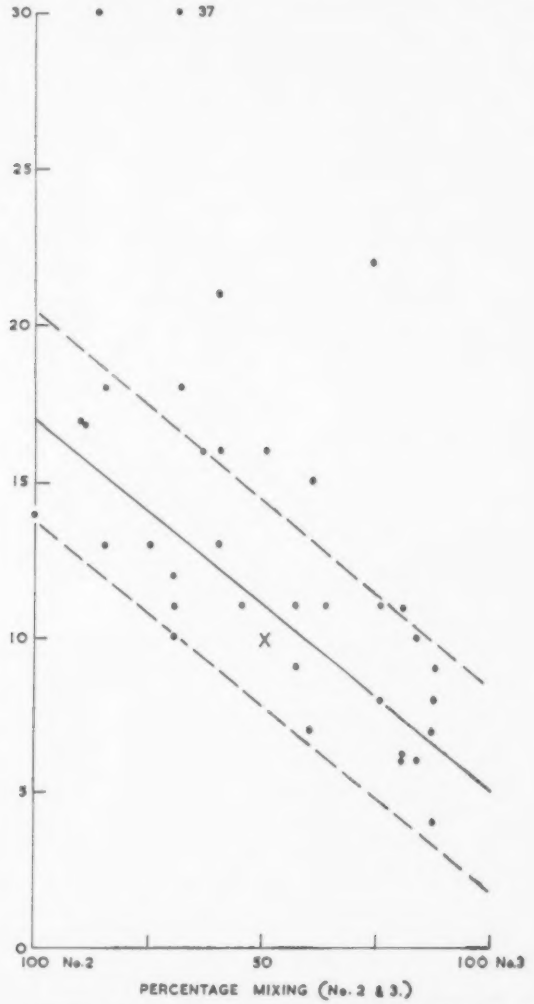

Fig. 13. The total phosphorus to water mass composition [(2) and (3) Table 1] of Tasman and Coral Sea surface waters. The cross shows the total phosphorus content of the South Equatorial water mass off Sydney.

of water masses (3) and (4). Using the mixing diagrams of Fig. 12 the total phosphorus to water mass composition of these waters was examined (Fig. 14). Water mass (4) was considered Central Tasman (ROCHFORD, 1957) and therefore should have a mean total phosphorus content of 16 with seasonal limits of 12 and 19 $\mu g/l.$ By using this mean value and that previously established for (3) a trend line was

fitted to Fig. 14. Within the limits of $\pm$ 3 μg/l., 70 per cent of values are associated with this trend line. If the positions of the stations at which the positive anomalies of total phosphorus in Figs. 13 and 14 occurred are plotted (Fig. 15) certain significant

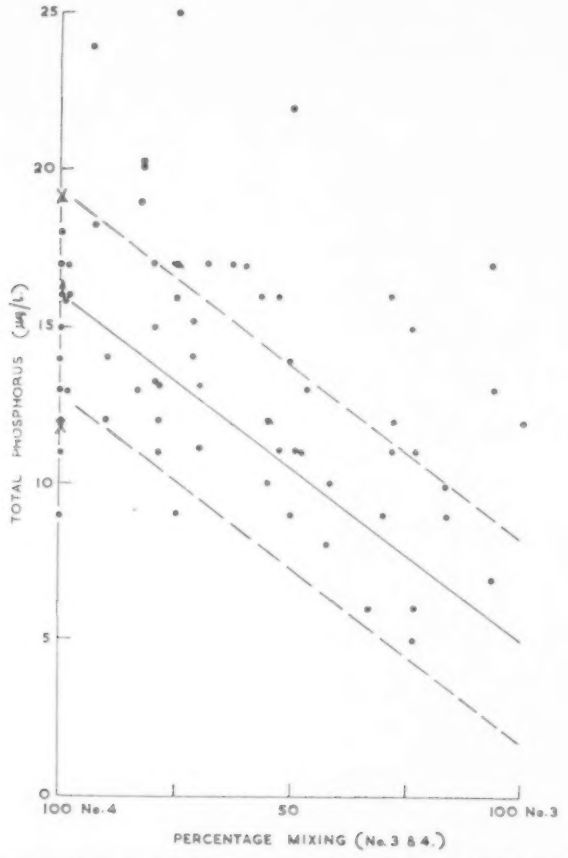

Fig. 14. The total phosphorus to water mass composition [(3) and (4) Table 1] of Tasman Sea surface water. The crosses show the annual limits of the total phosphorus content of the Central Tasman water mass off Sydney.

features are apparent. There seems no doubt that these positive anomalies in total phosphorus occurred wherever stations were worked close to certain regions of the continental shelf, Barrier Reef, oceanic island or submarine rises with depths less than 1,000 m.

As in eastern Bass Strait it seems probable from a comparison of Figs. 10 and 11 that these anomalies were developed along the paths of ocean currents represented by the East Australian current and of the Central Tasman water mass in November-December 1955, and of a westerly diversion of the East Australian current in April 1955. It seems possible therefore that turbulent stirring and transport of phosphate rich bottom sediments by Tasman Sea currents could be responsible for the total phosphorus anomalies in this region in November-December 1955.

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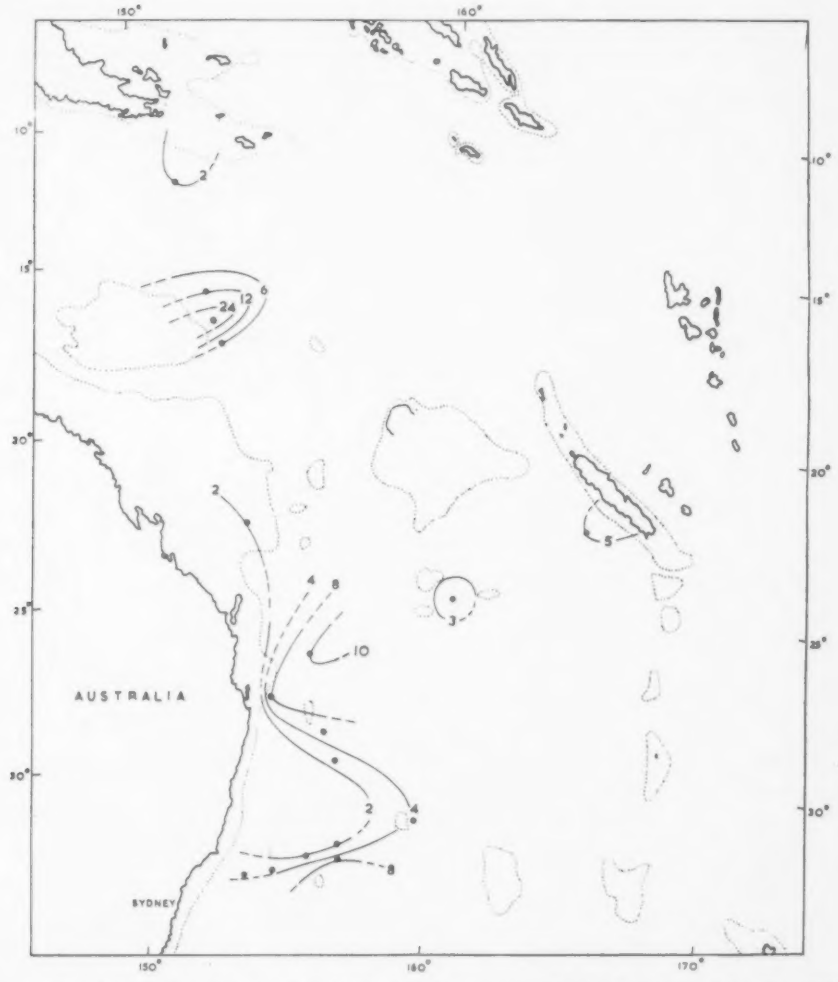

Fig. 15. The distribution of the positive total phosphorus anomalies in Figs. 13 and 14. The 1000 m contour has been entered to show the relation of shallow regions to these anomalies.

(*b*) *Intermediate Waters* 1954-56

The temperature-chlorinity characteristics of the waters of the Tasman and Coral Seas at depths of 300-500 m have remained relatively constant at all latitudes during the period of some 47 years separating the *Planet* station in 1910 from the *Derwent Hunter* station in 1957 (Fig. 16). Below 500 m however there is an increasing variation

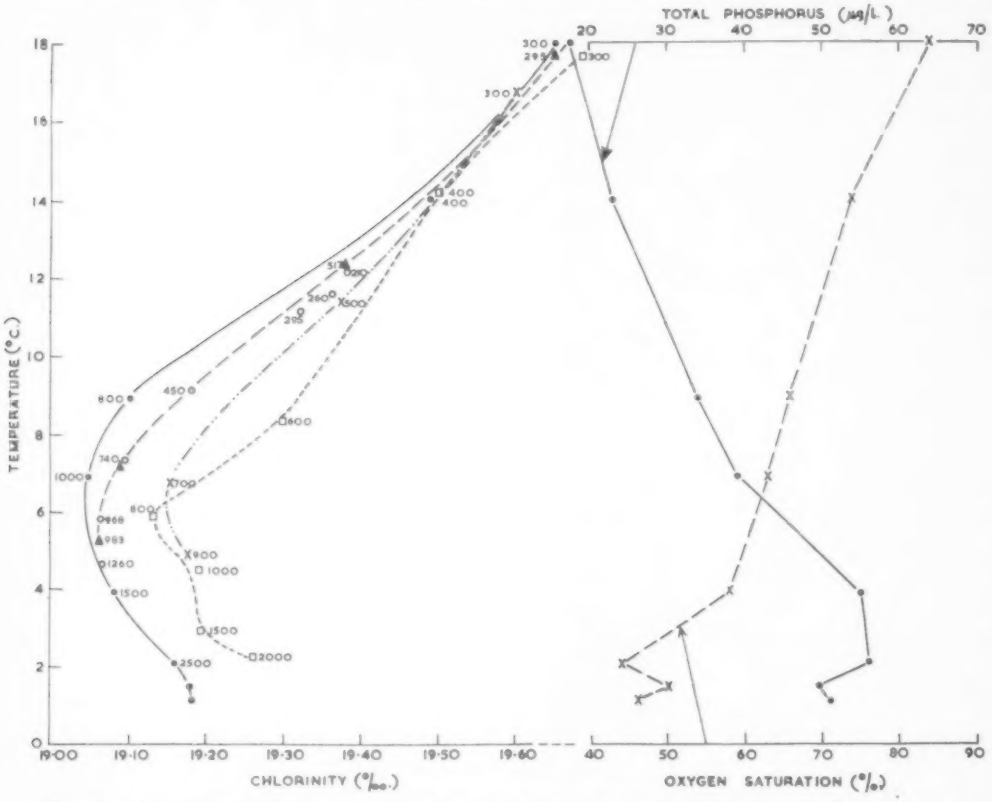

Fig. 16. The chlorinity-temperature curves for selected stations in the Coral and Tasman Seas.

□	*Planet Station*	55/10 – – – – – – 16°S
×	*Derwent Hunter*	179/55 – – – – – – 22°S
△	*Derwent Hunter*	183/55 – – – – – – 25°S
●	*Discovery* II	2726/50 – – – – – – 34°S
○	*Derwent Hunter*	1/57 – – – – – – 41°S

The vertical curves of total phosphorus and oxygen saturation have been drawn for station 2726 at the depth scale of its Cl‰ – temp. curve.

in these characteristics with maximum separation of the chlorinity-temperature curves just above the chlorinity minimum. This variation could be brought about by advection of different water masses or by geographical variations in the mixing processes at these depths. The geographic extent of this variation in recent years is shown in Fig. 17, in which the temperature of the 19·20‰ chlorinity surface lying above the chlorinity minimum has been charted. On the same chlorinity surface the field of oxygen saturation (Fig. 18) parallels that of temperature and suggests that similar physical processes control the distribution of oxygen at these depths.

The distribution of total phosphorus on the same chlorinity surface (Fig. 19) coincides with that of temperatures (Fig. 17) and it seems highly probable therefore that total phosphorus at these depths is similarly controlled.

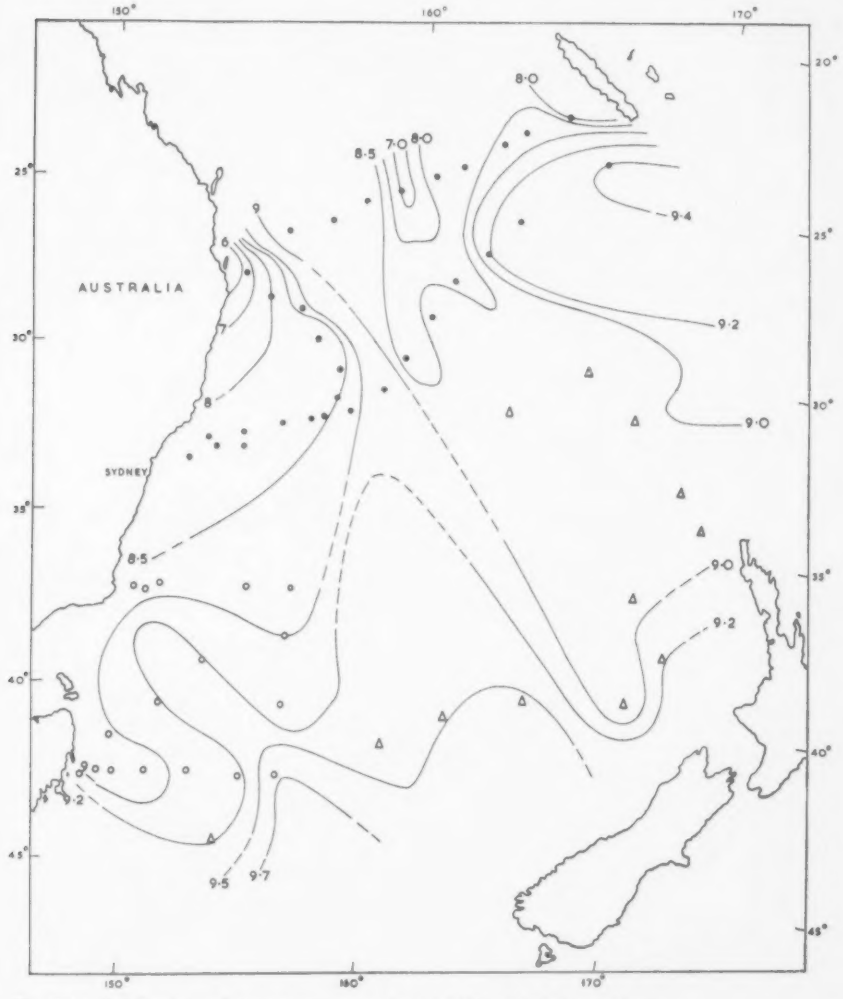

Fig. 17. The distribution of temperature on the 19·20‰ chlorinity surface.
○ . . . *Derwent Hunter*, November-December 1954.
● . . . *Derwent Hunter*, November-December 1955
△ . . . *Derwent Hunter*, December 1956 to February 1957.

By comparison of Figs. 15 and 19 some indication of a relationship between surface anomalies of total phosphorus and the region of occurrence of high total phosphorus in the intermediate layers during the November-December cruise can be found. It is possible therefore that turbulent stirring extends to these deeper levels and that mixing across the chlorinity minimum leading to a rise in total phosphorus and a

decrease in the degree of oxygen saturation (Fig. 16) is responsible for the geographical variation in the hydrological properties on the 19·20‰ chlorinity surface.

The difference in total phosphorus characteristics of the Pt. Hacking and Eden

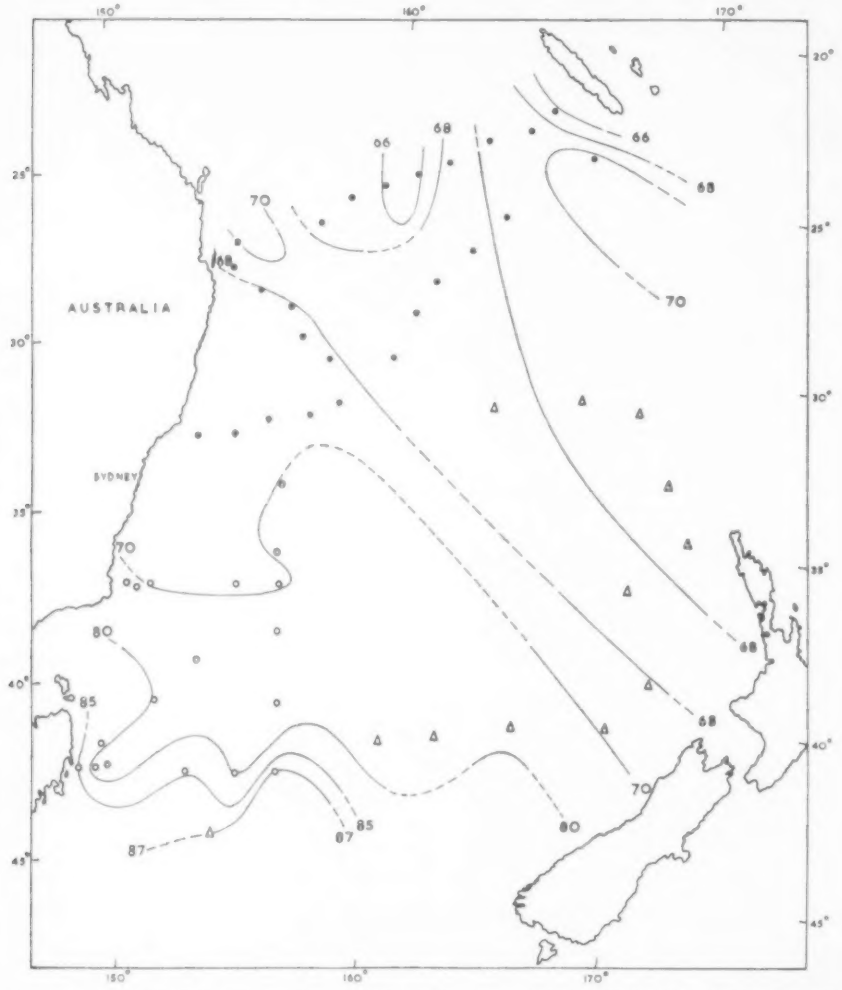

Fig. 18. The distribution of percentage oxygen saturation value on the 19·20‰ chlorinity surface.

slope waters (Fig. 7) parallels the gradient in their total phosphorus content at intermediate depths (Fig. 19). It is possible therefore that latitudinal variations in the extent of vertical mixing in these slope waters could be responsible for such differences.

V. DISCUSSION AND CONCLUSION

RITTENBERG *et al.* (1955) analysed the phosphorus content of certain marine sediments in basins off California. Using their values, it is possible to estimate the amount of marine sediment that would have to be carried to account for the

positive total phosphorus anomalies of East Australian waters. For an anomaly of 20 μg/l. a sediment load of 30 mg/l. would be necessary. As the highest value recorded by JERLOV (1953) for the open ocean had a scattering value of less than

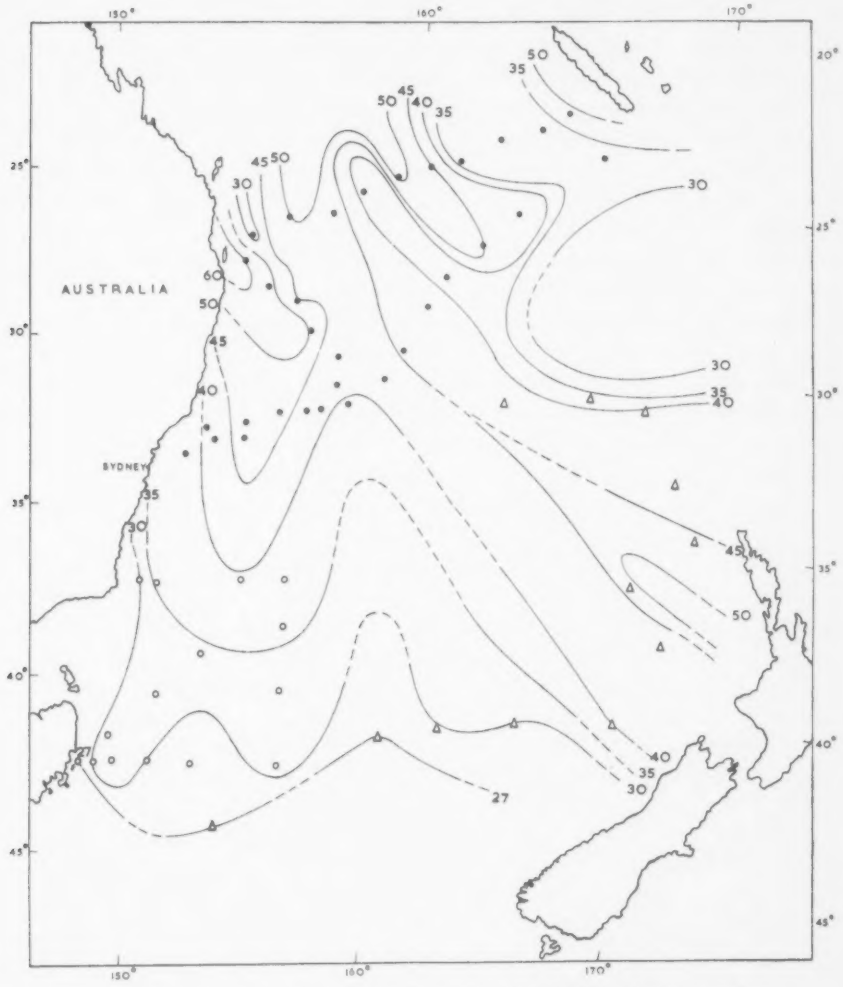

Fig. 19. The distribution of total phosphorus on the 19·20‰ chlorinity surface.

100, which according to a later paper (JERLOV and KULLENBERG, 1953), is developed by between 0·2 to 1·7 mg/l. of suspended matter, it does not seem possible that a single turbulent stirring of bottom sediments could be responsible. If, however, a repeated stirring of the bottom sediments and especially of their interstitial waters, which according to RITTENBERG *et al.* (1955) can contain up to 18 μg-a/l. of phosphates, occurred along the path of a current, an accumulated anomaly of the magnitude found in this investigation could be formed.

SESHAPPA (1953) analysed the phosphate content of mudbanks along the Malabar coast of W. India and found that the mud per unit volume contained " several

hundred times as much phosphate as the water-layer above it. Furthermore he found that the phosphate content of these coastal waters was greatly increased during the south-west monsoon of 1950, presumably by agitation of these phosphate rich muds.

DANNEVIG (1915) showed that, along the continental shelf of the east coast of Australia, there was a sub-division into a rocky section extending from the shore to about 100 m depth of water, which was separated by an abrupt wall of rock of about 40 m depth from a seaward portion covered by fine sand and mud which extended to the edge of the continental slope. He was of the opinion that the source of this fine sand and mud was the flood sediment load from the Tweed, Richmond and Clarence Rivers of northern New South Wales, which was carried south by the East Australian current and deposited on this part of the shelf. The bottom sediments of these rivers have a high total phosphorus content (C.S.I.R.O. 1952) and it could be that these fine sediments and their associated interstitial waters on the outer section of the shelf are responsible for the total phosphorus anomalies of New South Wales coastal waters.

During a period of flooding of New South Wales estuarine systems in the summer and autumn of 1955, considerable quantities of silt were carried seaward and transported south by the East Australian current. Off Sydney on March 31st, 1955, there was a steep seaward decline in surface total phosphorus values (Fig. 20). The

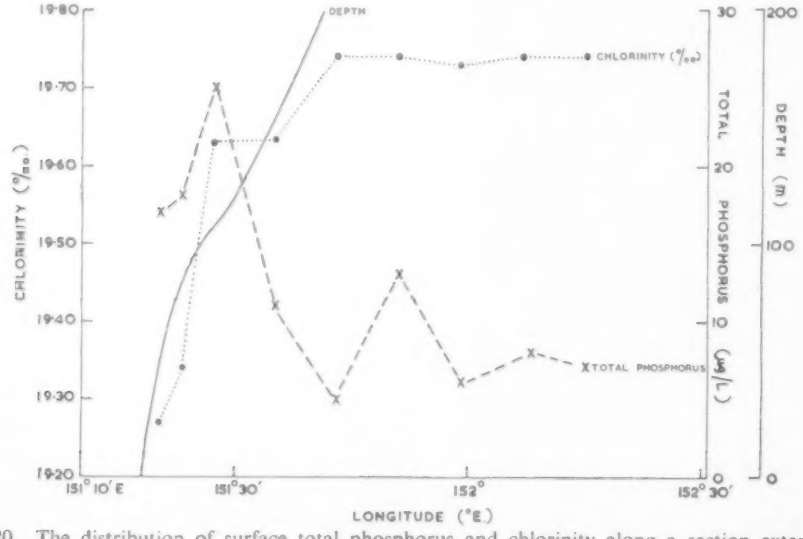

Fig. 20. The distribution of surface total phosphorus and chlorinity along a section extending 110°T from Sydney on the 29th to the 31st March, 1955. The depth profile along this section is also shown.

chlorinity distribution (Fig. 20) indicates that this decline in total phosphorus was probably brought about by a seaward movement and concentration of silt laden waters, along a boundary over the outer section of the shelf in waters of 150-200 m depth. This is in agreement with DANNEVIG's (1915) conclusion about the restriction of finest sediments to depths greater than about 150 m along the East Australian coast.

MILLER (1950) in a study of the mixing processes along the coastal regions of southern New England, U.S.A., has found slope water movements similar to those off Pt. Hacking and suggests that an internal wave which forms an internal surf at the edge of the shelf is the principal energy source. There seems no problem therefore regarding the energy source of turbulent stirring of coastal sediments. In the open ocean JERLOV (1953) found evidence of strong currents at Station 254 in the Red Sea, at depths approaching 2000 m. He also showed that accumulations of suspended matter occurred in the mid depths of the Atlantic along the Equator and suggested that these were caused by transport of sediments of the higher regions of the Atlantic Ridge. He also found that "the bottom suspension from adjacent rises in the bottom is distributed laterally by currents." It does not seem unreasonable therefore to conclude that turbulent stirring can occur down to depths of 1000-1500 m in the deeper waters of the Tasman and Coral Seas and that once an anomaly in total phosphorus is developed its effect can be made widespread by currents.

In Section IV (b) the variation in hydrological properties on the 19·20‰ chlorinity surface was ascribed to variations in the extent of turbulent exchange between the lower levels of the sub-Antarctic intermediate layer and the bottom waters of the Tasman Sea. This postulate necessitates only minor changes in the hydrological properties of the sub-Antarctic intermediate layer at its source, from one year to another. It is possible however that the original properties of the sub-Antarctic waters which sink to form this intermediate layer have varied greatly from year to year so that the Tasman Sea variation is a reflection of their past hydrological history in the Southern Ocean. If this be the case then these sub-Antarctic waters have varied in total phosphorus from 27 to 60 during the period represented by their present distribution in the Tasman Sea. Whilst such a variation does not invalidate the use of total phosphorus as a conservative identifying property of water mass distribution within the Tasman and Coral Seas, it does render its use less positive as an overall characteristic of it. On the evidence available the original explanation seems more acceptable but cannot be proven.

In Fig. 2 (b) the extent of oxygen supersaturation of the surface waters of the coastal and shelf stations indicates probably a high rate of photosynthesis associated with the onshore movement of these slope waters. Whether the increased supply of total phosphorus stimulates this over-saturation cannot be shown, but undoubtedly these slope water invasions must influence shelf productivity in general.

On the evidence of this paper therefore it is concluded that total phosphorus tends to be conservative in the Tasman and Coral Seas at both surface and intermediate depths, but that in regions of turbulence extending to the bottom, anomalies can occur. It is evident however from the amount of scatter in Figs. 13 and 14 that the degree of conservatism cannot be extended below limits of $\pm$2-3 μg/l. and that water masses differing in total phosphorus by less than 5 μg/l. cannot be distinguished by this property. Generally, too, it seems possible for the hydrologist to use anomalies in total phosphorus distribution to indicate regions of high vertical turbulence or waters which at some time in their history have contained bottom sediments in appreciable amounts.

Acknowledgments—Hydrological data can be collected only with the assistance of many persons, including crew members of ships as well as scientific colleagues, and to all of these grateful acknow-

ledgment is made. Particular acknowledgment however is made of the valuable data that is being collected by officers of M.V.'s "*Tulagi*" and "*Malaita*" in the Coral Sea.

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The frequency distribution of water characteristics in the Pacific Ocean

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(*Received* 1 *April* 1958)

Abstract—The bivariate distribution of water characteristics in the Pacific Ocean is studied using 155 hydrographic stations. Separate diagrams of potential temperature against salinity give the distributions for the North, the South, and the entire Pacific Ocean. The dominant feature in all the diagrams, an enormous mode near 1·5 C, 34·7 per mille, results largely from water below 2000 m. The mode is at 1·75 C in the South Pacific distribution. It is stronger in the North Pacific distribution and lies at 1·25 C. This lower temperature is surprising, but apparently explicable. A mode at 4·5 C, 34·55 per mille, Tropical Water, is due mainly to water between the Tropics at depths from 700m. to 1100 m. It is associated with a layer of minimum salinity extending through much of its region of occurrence. Two other waters characterized by extensive salinity minimum layers are represented by ridges in the distributions. These are identified and their relationships with Tropical Water discussed. Also discernible in the distributions are features representing the water of the thermocline layers above the salinity minimum layers. Surface layers account for most of the spreading of the distributions from the modes and important ridges. Unlike the Atlantic and Indian Oceans, the Pacific shows no modes which are far removed from the principal ones. Univariate distributions of characteristics are presented. Means and certain percentiles are tabulated.

INTRODUCTION

ALTHOUGH the temperature-salinity diagram has long been the most familiar means of comparing and classifying ocean waters, its suitability in representing bivariate frequency distributions of the water characteristics, temperature and salinity, has hardly been exploited. This aspect of the diagram is partially recognized when a large number of serial observations is plotted as a scatter diagram in temperature-salinity co-ordinates, as for example, by HELLAND-HANSEN and NANSEN (1926). But the first entirely quantitative representation of a distribution by means of the diagram seems to have been given by MONTGOMERY (1955) for surface temperatures and salinities at Weather Ship J.

In the present paper, the frequency distributions of Pacific water characteristics are presented in a series of diagrams. Distributions are given for the North and South Pacific separately as well as for the entire Pacific. The paper is one of a group of three forming an ocean-wide survey of water characteristics. It is the second paper by the author dealing with the frequency distribution of Pacific Water characteristics. The first (COCHRANE, 1956) was concerned with surface water.

The distributions presented are first approximations. Great accuracy is precluded by the scarcity of data in many parts of the Pacific Ocean, especially in the South Pacific. Reliable representation of major features, however, is an aim of the present study. No attempt was made to take account of seasonal or other time variation, although with bathythermograph data this seems possible for the North Pacific. Frequency is consequently expressed in terms of volume.

Table 1. List of Stations

Abbr.	*Name of Vessel or Organization*	*Station Nos.*	*No.*	*Year*	*Month*	*Source*
A	*Albatross*	52, 74, 87, 93, 105, 123, 128, 133, 138	9	1947	IX, X, XI, XII	BRUNEAU L. *et al.* (1953)
		143, 150, 157, 162	4	1948	I	
*B	*Bushnell*	a, f, j	3	1934	VIII	Manuscript on file at S.I.O.†
BB	*Brown Bear*	56-27, 64-6, 64-15, 64-45, 64-48	5	1954	V, VIII, X	COLLIAS E. C. *et al.* (1956)
C	*Carnegie*	37, 49, 55, 59, 61	5	1928	XI, XII	FLEMING J. A. *et al.* (1945)
		64, 66, 69, 72, 74, 76, 78, 81, 83, 87, 108, 109, 114, 116, 128, 132, 146, 152, 156	19	1929	I, II, III, V, VI, VII, IX, X, XI	
Ch	*Challenger*	1	1	1950	X	‡
		6, 7, 12	3	1951	III, IV	
*Cl	*Chelan*	107	1	1934	VIII	BARNES C. and THOMPSON T. G. (1938)
D	*Dana*	3558, 3561, 3563, 3564, 3577, 3580, 3585, 3620, 3624, 3628	10	1928	IX, X, XII	*Dana Report* No. 12 1937
		3653, 3656, 3665, 3685, 3690, 3696, 3714, 3724, 3880	9	1929	I, II, IV, V, VI, VIII	
Di	*Discovery* II	903, 920, 923, 949, 960, 962, 964, 967, 969, 970, 976, 978, 1000	13	1932	VI, IX, X, XI	*Discovery Reports*, Vol. XXI, 1942
		1255, 1280, 1283, 1291, 1297, 1453, 1464, 1473	8	1934	I, II, III, XI	ibid., Vol. XXII, 1943
		1669, 1684	2	1936	II	ibid., Vol. XXIV, 1947
		2192, 2208, 2217, 2226, 2238, 2268, 2288	7	1938	I, II, III	ibid., Vol. XXIV, 1947
*Kh	*Komahasi*	68 (Japanese Navy Cruise 24)	1	1933	IX	*Hydrogr. Bull., Tokyo*, Special No., 1950
		72§ (J. N. Cr. 38)	1	1936	VIII	ibid., 1951
		52, 72§ (J. N. Cr. 44)	2	1937	VI	ibid., 1951
*Kr	*Katuriki*	11 (J. N. Cr. 35)	1	1935	XI	ibid., 1951
		10 (J. N. Cr. 40)	1	1936	V	ibid., 1951
*Ks	*Kosyu*	11, 40, 41 (J. N. Cr. 27)	3	1933	IV, VIII	ibid., 1950
		B84 (J. N. Cr. 32)	1	1935	II	ibid., 1950
		32, 78, 87 (J. N. Cr. 36)	3	1935	VII, VIII	ibid., 1950
*N	*Northland*	109	1	1937	VII	GOODMAN J. R. *et al.* (1942)
S	S. I. O. Misc. cruises	1949-C6-1011 (*Crest*)	1	1949	VIII	*MLR Program Data Report* No. 6, 1950
		5404F-140.150 (*Baird*)	1	1954	IV	Manuscript on file at S.I.O.
S VII	*E. W. Scripps* Cruise VII	27	1	1939	III	*Rec. Obns. Scripps Instn. Oceanogr.* 1 (2), 1943
SAT	S. I. O. Operation ACAPULCO TRENCH	16, 19, 22	3	1954	XII	Manuscript on file at S.I.O.
SC	S.I.O. Operation CUSP	A	1	1954	VII	Manuscript on file at S.I.O.
SNP	S.I.O. Operation NORPAC	11, 43, 63, 82, 149, 153, 157	7	1955	VIII, IX	*Scripps Instn. of Oceanogr.* Ref. 56-4, 1956
STP	S.I.O. TRANSPAC Expedition	11d, 20d, 24, 30, 38, 42, 49, 52, 59, 63, 64, 68, 96, 99, 103, 112, 120, 132	18	1953	VII, VIII, IX, X, XI	Manuscript on file at S.I.O.
Sc	*William Scoresby*	601, 736, 737	3	1931	V, VIII	*Discovery Reports*, Vol. XXV, 1949
Sm	*Hugh M. Smith*	5-3, 5-38	2	1950	VII, VIII	CROMWELL T. (1954)
Sn	*Willebrord Snellius*	52	1	1929	VIII	VAN RIEL P. M. *et al.* (1950)
		248	1	1930	IV	
*Y	*Yamato*	26, 36, 40 (J. N. Cr. 21)	3	1932	VI	*Hydrogr. Bull., Tokyo*, Special No., 1950
		Total	155			

*Only interpolated values were available.
†Scripps Institution of Oceanography.
‡Pacific & Indian Oceans and the Mediterranean Sea, temperature, salinity, and density of the sea-water from observations by H.M.S. *Challenger* 1950-1952. Hydrographic Dept., Admiralty, London.
§On chart showing location of stations, *Komahasi* Station 72 of Japanese Navy Cruise 38 is abbreviated as '36KH72, and station 72 of Cruise 44 as '37KH72.

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Fig. 1. Location of stations. Circles represent stations used at all depths, X's stations used only at greater depths. A, *Albatross* ; B, *Bushnell* ; BB, *Brown Bear* ; C, *Carnegie* ; Ch, *Challenger* ; Cl, *Chelan* ; D, *Dana* ; Di, *Discovery* II ; Kh, *Komahasi* ; Kr, *Katuriki* ; Ks, *Kosyu* ; N, *Northland* ; S, Scripps Institution of Oceanography (S.I.O.), miscellaneous ; S VII, E. W. Scripps, Cruise VII ; SAT, S.I.O. Operation ACAPULCO TRENCH ; SC, S.I.O. Operation CUSP ; SNP, S.I.O. Operation NORPAC ; STP, S.I.O. TRANSPAC Expedition ; Sc, *William Scoresby* ; Sm, *Hugh M. Smith* ; Sn, *Willebrord Snellius* ; Y, *Yamato*.

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METHOD

The definitions of the Pacific Ocean and the North and South portions follow those given in *Die Grenzen der Ozeane und ihre Nebenmeere* (ANON., 1939). Adjacent seas are included.

Estimates of the distributions are based on a selected group of hydrographic stations. Each pair of temperature and salinity values at a station is taken as typical of a volume surrounding the pair. The magnitude of the volume depends on the vertical and horizontal spacing between observations. The volumes typified by characteristics within selected intervals are totalled to obtain the distribution of volume among characteristics.

Ideally, the selected stations would be uniformly spaced and would reach to the bottom. Actually, such a group cannot be approximated even roughly in the Pacific Ocean unless the spacing is so wide that many well established features of the temperature and salinity structure are ignored. Sampling known important features is favoured over uniform spacing.

The stations on which this study is based are listed in Table 1 and their locations shown in Fig. 1.

Wherever possible, observed rather than interpolated values are employed. For some localities, however, only the interpolated values at hydrographic stations are published. There are 22 such stations used in the present study.

As many of the stations selected do not reach to sufficient depth, values from neighbouring stations are used. In seven cases deep values are taken from stations which are not suitable for representation of the shallower layers. These stations are indicated in Fig. 1.

Table 2. Volume distribution of potential specific volume anomaly. Volume in 10^4 *km*^{3}

Potential specific volume anomaly, in cl t^{-1}	*Portion of Pacific Ocean*			*Potential specific volume anomaly, in cl t*$^{-1}$	*Portion of Pacific Ocean*		
	Entire	*North*	*South*		*Entire*	*North*	*South*
0– 9	0	0	0	0– 49	48451	23805	24646
10– 19	328	25	303	50– 99	14478	6236	8242
20– 29	14637	5209	9428	100–149	5439	2345	3094
30– 39	22667	13559	9108	150–199	1399	814	585
40– 49	10819	5012	5807	200–249	749	439	310
				250–299	555	255	300
50– 59	3550	1556	1994	300–349	336	197	139
60– 69	3718	1833	1885	350–399	307	191	116
70– 79	2940	1485	1455	400–449	189	132	57
80– 89	2258	806	1452	450–499	149	96	53
90– 99	2012	556	1456	500–549	153	97	56
				550–599	127	102	25
100–109	2328	724	1604	600–649	67	36	31
110–119	1128	438	690	650–699	8	8	0
120–129	792	417	375	700–749	2	2	0
130–139	759	476	283	750–799	1	1	0
140–149	432	290	142	800–849	1	1	0
				850–899	2	2	0

Boundaries between regions surrounding hydrographic stations are located partly for convenience and partly on the basis of established features of the fields of temperature and salinity. Some attempt is also made to select boundaries which keep the depth of each region fairly uniform.

The volume assumed to be typified by a pair of temperature and salinity values is determined by the following procedure. The area of a region is obtained by planimetering on an equiareal chart. The depth for a given pair extends between the midpoint to the next pair above and the midpoint

below, or, if the pair is at the top or bottom of a series, between the top or bottom and the mid-point to the next pair. The bottom of a region is taken at the average depth of the region as visually estimated from a bathymetric chart of the Pacific.

The sum of the volumes obtained by the above procedure is 72413 × 10^4 km^3. This may be compared with KOSSINA's more precise value of 72368 × 10^4 km^3 for the entire Pacific Ocean.

Since waters from all depths are treated together in this study, potential temperature is employed rather than temperature *in situ*. Thus the effect of depth on temperature is eliminated inasmuch as the potential temperature of a water parcel is the temperature it will acquire when its pressure is reduced adiabatically to atmospheric pressure. Potential temperatures are computed by means of nomograms prepared by MONTGOMERY and POLLAK on the basis of HELLAND-HANSEN's (1930) computations.

The class intervals used in the bivariate distributions represent compromises

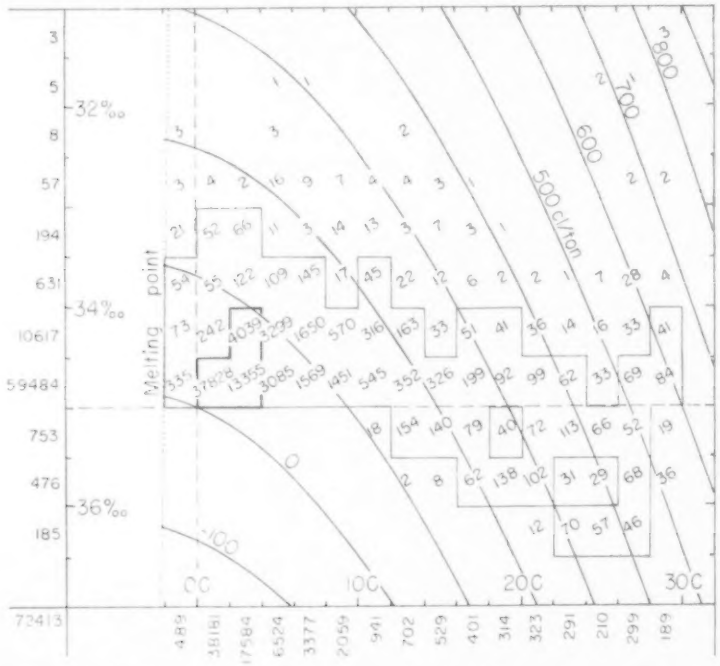

Fig. 2(a). The bivariate distribution of volume among potential temperatures and salinities for the entire Pacific Ocean. Sloping numbers give the volume of water in 10^4 km^3 for each class 2C × 0·5 per mille. Sums at the bottom give the distribution by potential temperature alone, sums at the left by salinity alone. The heavy boundary encloses classes comprising 75 per cent of the volume of the entire Pacific Ocean (classes with 4039 × 10^4 km^3 or more). The light boundary encloses classes comprising 99 per cent (classes with 45 × 10^4 km^3 or more). Potential specific volume anomaly is represented by the curves.

between the detailed information of small intervals and the reliability of large intervals. Since the sample is relatively large at low potential temperatures, small intervals can be employed. These intervals are clearly unsuitable for the entire range. Consequently two sets of intervals are used, finer classes, 0·5 C × 0·1 per mille, for water colder than 10 C and saltier than 32·5 per mille and coarser classes, 2 C × 0·5 per mille, for the entire range, that is, classes 20 times as large as the finer ones.

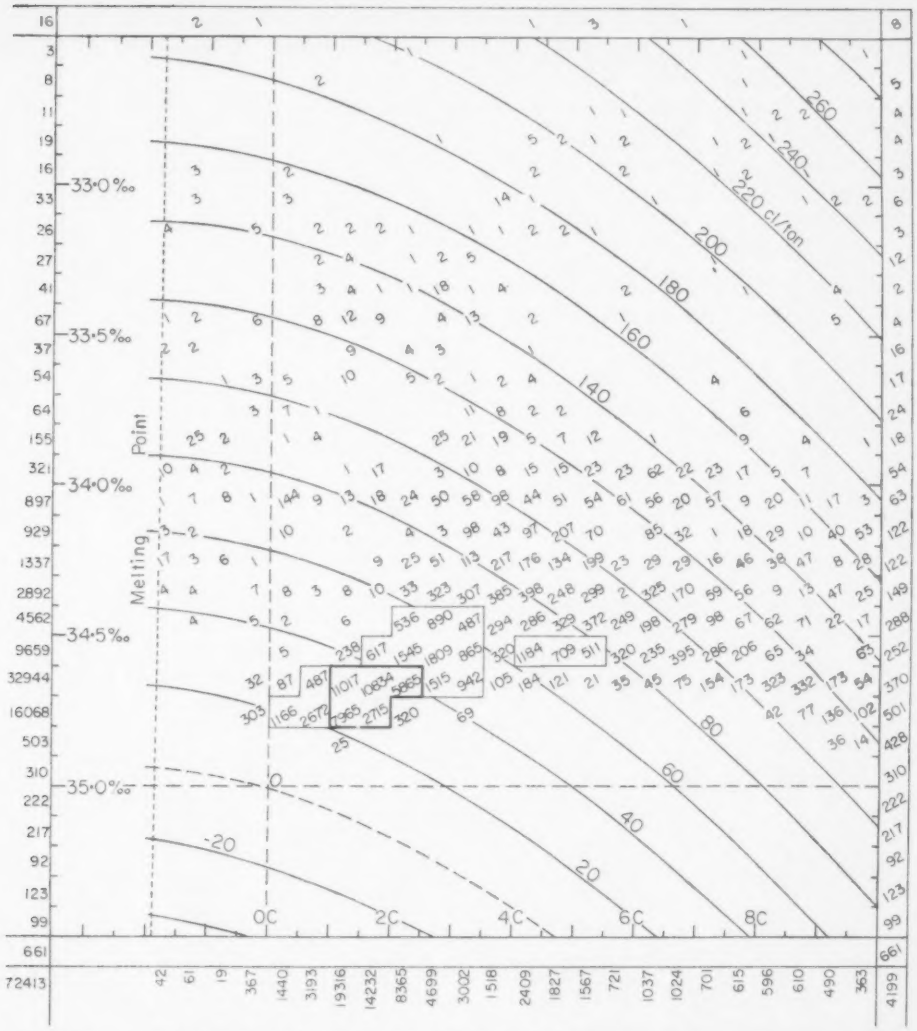

Fig. 2(b). Magnified portion of the bivariate distribution of volume among potential temperatures and salinities for the entire Pacific Ocean. Sloping numbers give the volume of water in 10^4 km^3 for each class 0·5 C × 0·1 per mille. Water outside of the range of the diagram is represented by sloping numbers in the bands at the top and right. Sums at the bottom give the distribution by potential temperature alone, at the right by salinity alone. The heavy boundary encloses classes comprising 50 per cent of the volume of the entire Pacific Ocean (classes with 2715 × 10^4 km^3 or more). The light boundary encloses classes comprising 75 per cent (classes with 487 × 10^4 km^3 or more). Potential specific volume anomaly is represented by the curves.

The distribution for the entire Pacific Ocean is presented in Figs. 2(a) and 2(b), for the North Pacific in Figs. 3(a) and 3(b), and for the South in Figs. 4(a) and 4(b). The "a" designates the diagrams with coarser classes which cover the entire range, the "b" designates the diagrams magnifying the limited range with the finer classes. Column and row totals are entered in the diagrams so as to give the univariate distributions of potential temperature and salinity. The entries in the diagrams are

volumes in units of 10^4 km^3. The values are recorded to single units to facilitate accounting, although they can scarcely be accurate to better than a few per cent.

In the diagrams, various boundaries are entered each of which encloses classes whose combined volume just exceeds a stated proportion of the total volume of the Pacific. Since each of these boundaries is also taken to be a volume isopleth, it is unique and encloses the smallest number of classes whose combined volume exceeds the stated proportion.

Potential specific volume anomaly is represented in the diagrams by isopleths. Table 2 gives its distributions. Two sets of intervals are employed, fine intervals of 10 cl t^{-1} for values below 150 cl t^{-1} and coarse intervals of 50 cl t^{-1} for the whole range. The distributions are derived from the fine-scale bivariate distributions*.

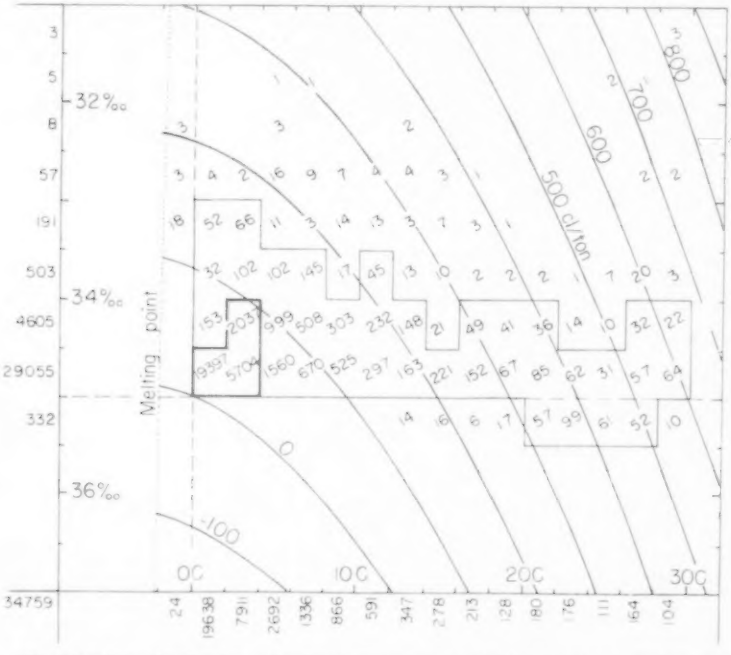

Fig. 3(a). The bivariate distribution of volume among potential temperatures and salinities for the North Pacific Ocean. Sloping numbers give the volume of water in 10^4 km^3 for each class 2C × 0·5 per mille. Sums at the bottom give the distribution by potential temperature alone, sums at the left by salinity alone. The heavy boundary encloses classes comprising 75 per cent of the volume of the North Pacific Ocean (classes with 2037 × 10^4 km^3 or more). The light boundary encloses classes comprising 99 per cent (classes with 22 × 10^4 km^3 or more). Potential specific volume anomaly is represented by the curves.

In the derivation, the entire volume of a bivariate class is considered to have the potential specific volume of its centre.

DISCUSSION

Principal features of the distribution for the entire Pacific. In order to provide a basis for further discussion, some prominent features of the distribution for the

*Fine distributions covering the entire range were compiled although only limited portions are presented in this paper.

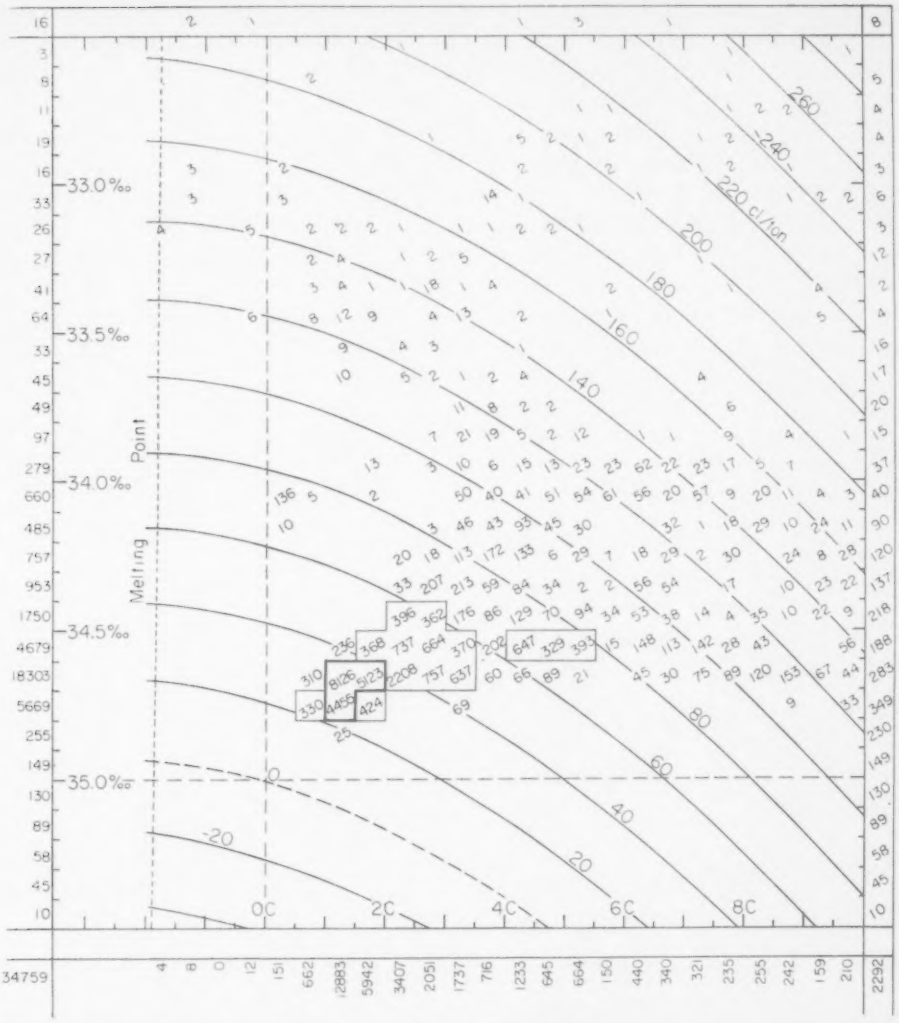

Fig. 3(b). Magnified portion of the bivariate distribution of volume among potential temperatures and salinities for the North Pacific Ocean. Sloping numbers give the volume of water in 10^4 km^3 for each class 0·5 C × 0·1 per mille. Water outside of the range of the diagram is represented by sloping numbers in the bands at the top and right. Sums at the bottom give the distribution by potential temperature alone, at the right by salinity alone. The heavy boundary encloses classes comprising 50 per cent of the volume of the North Pacific Ocean (classes with 4455 × 10^4 km^3 or more). The light boundary encloses classes comprising 75 per cent (classes with 329 × 10^4 km^3 or more). Potential specific volume anomaly is represented by the curves.

entire Pacific are described and their geographic counterparts mentioned. A few new names are introduced when they seem important for clarity.

One feature of the distribution dwarfs all others, the gigantic mode at 1·5 C, 34·65 per mille (potential specific volume anomaly 35 cl t^{-1}). The fine-scale diagram (Fig. 2b) clearly shows how great the concentration about this point is, 33 per cent of the volume having characteristics between 1 and 2 C and between 34·6 and 34·7 per mille, only two of the fine-scale classes. The 50-per-cent boundary (indicating

a volume greater than that of the entire Atlantic Ocean) encloses only five classes. The water within these fills the Pacific below a few hundred metres in its Antarctic regions and below roughly 2000 m elsewhere. The name Deep Water will be used to designate water within or very near the 50-per-cent boundary.

The 75-per-cent boundary further emphasizes the degree of homogeneity of the Pacific, only 20 classes lying within it. Of these, 17 form a single group including the five within the 50-per-cent boundary. There are no subsidiary maxima within this group. Three classes form an extension below 1·0 C from the 50-per-cent boundary and nine bulge from the boundary toward higher temperature and somewhat lower salinity.

The three classes bounded by the second closed portion of the 75-per-cent line constitute a secondary mode with a peak at 4·25 C, 34·55 per mille (65 cl t^{-1}). Most

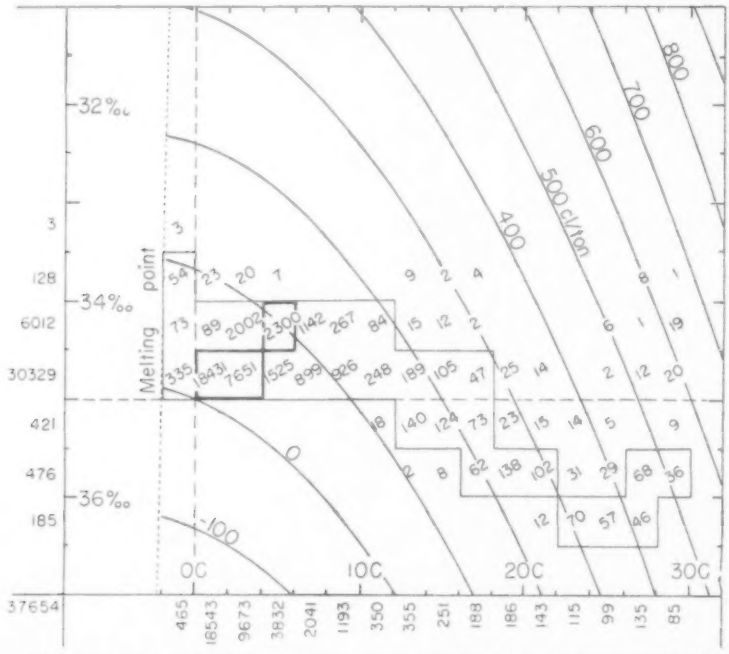

Fig. 4 (a). The bivariate distribution of volume among potential temperatures and salinities for the South Pacific Ocean. Sloping numbers give the volume of water in 10^4 km^3 for each class 2 C × 0·5 per mille. Sums at the bottom give the distribution by potential temperature alone, sums at the left by salinity alone. The heavy boundary encloses classes comprising 75 per cent of the volume of the South Pacific Ocean (classes with 2300 × 10^4 km^3 or more). The light boundary encloses classes comprising 99 per cent (classes with 36 × 10^4 km^3 or more). Potential specific volume anomaly is represented by the curves.

of the water represented by the three classes occupies a region extending across the ocean between the Tropics and reaching from 700 m to as deep as 1100 m. The water is therefore called Tropical Water. Some of it is found in a rather thin layer extending from the Tropical region along the coast of the Americas to latitudes of somewhat more than 30°. It also occurs in the western South Pacific north of 50°S at depths between 900 m and 1200 m.

A third mode appears at 0·25 C, 34·05 per mille (75 cl t^{-1}). Nearly all of this water

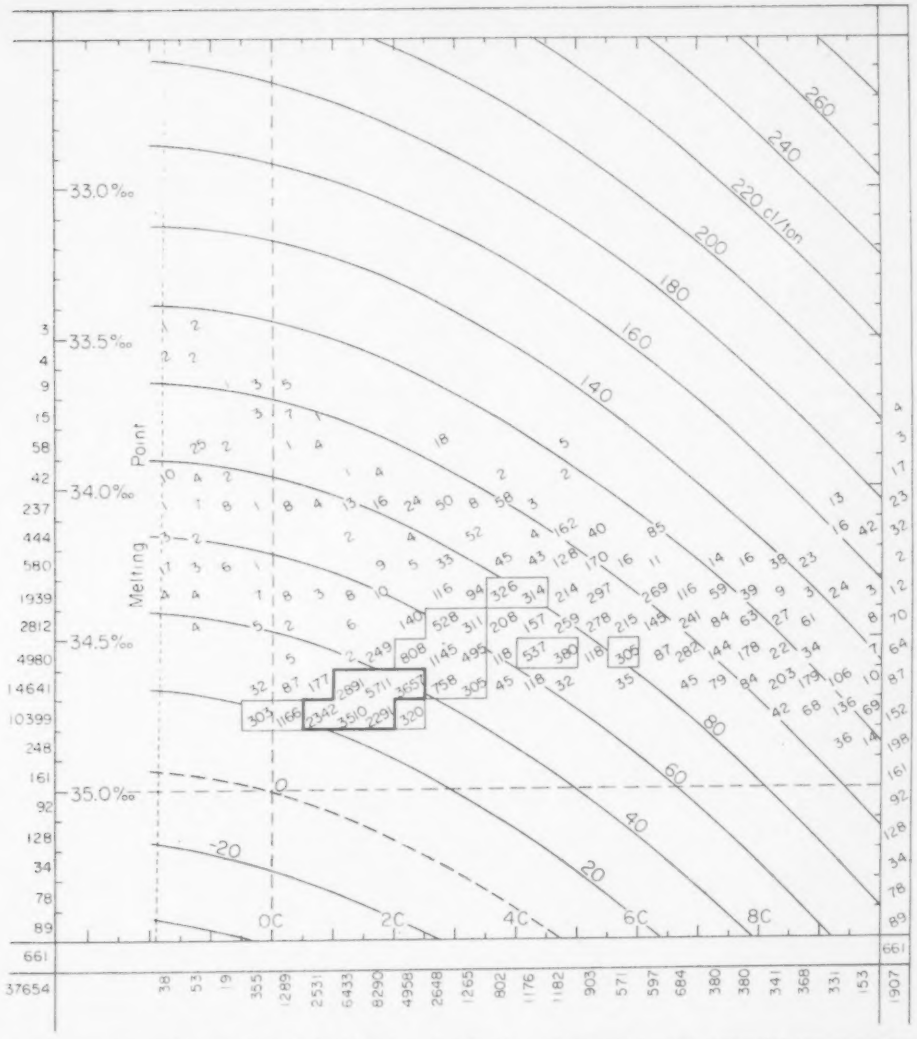

Fig. 4(b). Magnified portion of the bivariate distribution of volume among potential temperatures and salinities for the South Pacific Ocean. Sloping numbers give the volume of water in 10^4 km^3 for each class 0·5 C × 0·1 per mille. Water outside of the range of the diagram is represented by sloping numbers in the bands at the top and right. Sums at the bottom give the distribution by potential temperature alone, at the right by salinity alone. The heavy boundary encloses classes comprising 50 per cent of the volume of the South Pacific Ocean (classes with 2291 × 10^4 km^3 or more). The light boundary encloses classes comprising 75 per cent (classes with 303 × 10^4 km^3 or more). Potential specific volume anomaly is represented by the curves.

occurs in the Sea of Japan between about 400 m and the bottom, although a little is found in the upper layers of the Antarctic region. This water is formed at the surface during cold winters. It is of interest because it is the only water unquestionably of Pacific origin which reaches to considerable depths – the bottom of the Sea of Japan. It attains these depths only because the denser water of the main basin of the Pacific cannot enter the Sea of Japan.

From the coarse-scale diagram of Fig. 2 (a), it is possible to see the general outlines of the distribution. It consists largely of a rather broad ridge extending from the primary mode toward higher potential temperatures and somewhat higher salinities. In most cases, the crest of the ridge lies near the highest salinity for a temperature. Above 18 C, the ridge separates into two branches, as the 99-per-cent boundary shows. The one at lower salinities represents the North Pacific and the one at high salinities the South. In both branches, maximum salinities are found between 22 C and 26 C. Lowest salinities appear at potential temperatures below 10 C and above 24 C.

There are no detached modes at high salinities in the Pacific distribution. In this regard the Pacific distribution differs from both the Atlantic Ocean distribution given by MONTGOMERY (1958) and the Indian Ocean distribution given by POLLAK (1958). No seas adjacent to the Pacific correspond to the Mediterranean or to the Red Sea, where very salty water forms. Some, indeed, is formed in the northern parts of the Gulf of California, but in amounts which are inappreciable for the present study.

The Deep Water. The Deep Water of the Pacific appears to consist of water imported into the Pacific by the Antarctic Circumpolar Current and very similar forms which result from the mixing of the Circumpolar Water with less salty water above and possibly from warming of the deepest layers due to heat flow through the floor of the Ocean. Water with the characteristics of Deep Water does not appear in appreciable quantity at the surface according to the statistics given by COCHRANE (1956). It is possible that small amounts are formed along the Pacific coast of the Antarctic in a manner similar to that occurring in the Weddell Sea (SVERDRUP *et al.*, 1942). Such amounts must be very small in view of the relative rarity of water with potential temperatures less than 0 C. Except for this possibility there seems to be no source of water sufficiently dense to reach great depths in open portions of the Pacific.

Where the Deep Water enters the Pacific, its upper layers are saltier than those at the bottom, 34·75 to 34·76 per mille compared to about 34·70 per mille at the bottom. In the present study, nearly all stations at which salinity as high as 34·75 per mille appears in the Deep Water are at the " Antarctic Convergence " or farther south. Within this group there is apparently a slight decrease in salinity toward the east, that is, in the direction of flow of the Antarctic Circumpolar Current. At nearly all stations to the north of the " Convergence," the higher salinity values do not appear, probably because of mixing with the less saline water above. Salinity of 34·75 per mille is recorded in the upper Deep Water layers at *Dana* Station 3656, which is at 33°S in the Tasman Sea, far to the north of the " Convergence," but near the region where the Deep Water enters the Pacific Ocean. Higher salinities appear in three observations below 2470 m at *Discovery* Station 1280. Since high values extend all the way to the bottom, the observations are difficult to interpret.

As is pointed out by MONTGOMERY (1958), the Deep Water of the Pacific is the most nearly homogeneous occurring in any of the oceans. This is due in part to the lack of important sources of water with comparable density – and with slightly different characteristics. It results also from the mixing of the upper layers of the Deep Water with less salty water which brings the salinity of the upper layers of Deep Water nearly to that of the deeper layers. The greatest uniformity of Deep Water is thus achieved in the ocean farthest from its main sources.

The degree of uniformity of Deep Water is even greater than is indicated by the distributions (Figs. 2b, 3b, and 4b). Actually, the bulk of salinities lies between 34·67 and 34·72 per mille. But because the division between intervals falls at 34·70 per mille, the volumes are split between two intervals with a total range nearly twice the one actually appearing in the observations.

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Within the Pacific Ocean, greater uniformity is found in the North. The 50-per-cent boundary encloses only three classes of the fine-scale distribution for the North (Fig. 3b), but six classes for the South (Fig. 4b). The 75-per-cent boundary shows a similar difference, enclosing 17 classes for the North and 21 for the South. It may be noted that the ratio of the number of classes within the 75-per-cent boundary to the number of classes within the 50-per-cent boundary is nearly 5·7 for the North, but only 3·5 for the South. The North distribution might thus be characterized as more peaked than the South. On the basis of values given by MONTGOMERY (1958), it is found that this ratio is about 4·0 for each of the major Oceans, the Pacific, the Atlantic, and the Indian.

The 50-per-cent boundaries for North and South Pacific lie between salinities of 34·6 and 34·8 per mille. The boundary extends from 1 C to 2 C in the North Pacific distribution and to both lower and higher temperatures in the South, 0·5 C and 2·5 C, respectively. The modal class for the North Pacific is centred at 1·25 C, 34·65 per mille, the modal class for the South at 1·75 C, 34·65 per mille.

It is not surprising to find that the proportion of water colder than 1·0 C is less in the North than in the South Pacific, since in travelling northward from the South Pacific, the coldest water might be expected to mix in some degree with the warmer water above. However, the proportion changes from 11 per cent in the South to two per cent in the North Pacific, a very large decrease. Examination of the stations used in the present study discloses that, below 4000 m in much of the North Pacific, the potential temperature becomes constant at slightly more than 1·0 C, while, in the South Pacific, it almost always decreases with depth all the way to the bottom. The decrease in the proportion below 1·0 C thus does not seem to arise from mixing alone. Two other influences on the deep temperature structure have been pointed out by WOOSTER and VOLKMANN*. One is the deep sills which apparently cut much of the North Pacific off from the South Pacific and prevent the flow of the coldest South Pacific water into the North Pacific. The other is heating through the ocean floor.

It is surprising to find that the proportion of water colder than 1·5 C is much greater in the North, 39 per cent, than in the South Pacific, 28 per cent. The proportion of colder water increases downstream from the source of cold water. This odd circumstance arises because the 1·5 C surface lies, in general, at a shallower depth in the North than in the South Pacific except in the region south of the Antarctic Convergence (described, for example, by SVERDRUP *et al.*, 1942). Between 40°S and the Equator, most of the stations of the sample reach 1·5 C below 3000 m. On the other hand, few of the North Pacific stations fail to reach 1·5 C above 3000 m.

Compensation for the greater proportion of the North Pacific with temperature below 1·5 C is effected largely within the range of temperatures from 1·5 C to 3·0 C, where only 33 per cent of the North Pacific water, but 42 per cent of the South Pacific water is found. The layer from the 1·5 C to the 3·0 C surface is evidently much thinner in the North Pacific. Possibly, this difference results from a less effective means of carrying warmer water down from the upper layers in the North Pacific. The North Pacific counterpart of the Southern Intermediate Water, which is described

*In a paper presented at the Symposium on Abyssal Circulation (International Association of Physical Oceanography, International Union of Geodesy and Geophysics), Toronto, 5-6 September 1957.

below, may not carry as much heat down with it. Another possibility, however, is that, within the layer with temperatures from 1·5 C to 3·0 C, greater vertical convergence occurs in the North than in the South Pacific.

The transitions to the waters above Deep Water are shown by features appearing in the 75-per-cent boundary surrounding the primary mode. In the South Pacific distribution (Fig. 4b) classes within this boundary extend from the 50-per-cent boundary along a roughly linear ridge to the vicinity of 4·0 C, 34·35 per mille. The detached classes within the 75-per-cent boundary are joined to the main body of classes within the boundary more from the end of the ridge described above than by a ridge extending directly to them from the main body.

The classes within the 75-per-cent boundary surrounding the primary mode of the North Pacific distribution (Fig. 3b) do not constitute a single ridge towards higher temperature from the 50-per-cent boundary, but rather two ridges. The extension of one of the ridges connects the detached classes within the 75-per-cent boundary, Tropical Water, directly to the main body surrounding the primary mode at 34·55 per mille. The other runs along a line from 2·25 C, 34·55 per mille to the vicinity of 5·0 C, 34·0 per mille.

Intermediate Waters. In the Pacific there are a number of extensive layers typified by a minimum of salinity with depth. It is convenient to refer to the waters with the characteristics occurring in any of these layers as Intermediate Waters. The Intermediate Water most clearly shown in the diagrams (Figs. 2b, 3b and 4b) is the Tropical Water described above, which constitutes the secondary mode in each of the distributions.

In the stations used in the present study, the salinity minimum associated with the Tropical Water is found usually at potential temperatures somewhat above 5 C, that is, at potential specific volume anomalies of 75 cl t^{-1} or somewhat higher. Since the peak of Tropical Water is at 4·25 C (65 cl t^{-1}), the greater part of Tropical Water lies below the salinity minimum. This evidently results from the fact that the salinity increase with height above the minimum is greater than the increase with depth below it.

Not all of the Tropical Water is typified by a salinity minimum. West of about 150°W and north of about 10°N, it is overlain by water of still lower salinity, Northern Intermediate Water, which will be described later.

In the South Pacific distribution (Fig. 4b), there is a broad ridge extending between 70 and 95 cl t^{-1} from 3·5 C to 6·0 C, that is, from the high-temperature end of the main 75-per-cent boundary to the detached 75-per-cent boundary representing Tropical Water. Water with these characteristics will be called Southern Intermediate Water.

Most of the volumes making up the ridge are associated with the minimum of salinity with depth which covers the South Pacific north of the Antarctic Convergence. (This feature is described, for example, by SVERDRUP *et al.*, 1942.) Most of the depths at which the minimum is found fall between 400 and 1000 m. The minimum is distinct in a region bounded on the south roughly by a line from 50°S in the longitude of Tasmania (145°E) to 25° at the South American coast. Between this line and the Antarctic Convergence, the minimum is not always clear because the water above it has nearly as low salinity.

In the distribution (Fig. 4b), the classes representing Southern Intermediate Water merge with the classes representing Tropical Water. The stations of the

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present study do not indicate that the salinity minimum suddenly changes its depth or potential specific volume anomaly in going from the Southern Intermediate Water to Tropical Water. Much of the latter appears to be only a modification of Southern Intermediate Water produced by mixing with the saltier waters above and below. Tropical Water of lowest temperature (4·25 C, 34·55 per mille, 65 cl t^{-1}), however, does not fall within the specific volumes typifying Southern Intermediate Water.

According to SVERDRUP *et al.* (1942), water of 2·2 C, 33·8 per mille (about 105 cl t^{-1}) sinks at the "Antarctic Convergence" and mixes with saltier water to produce Southern Intermediate Water (called Antarctic Intermediate Water by SVERDRUP) in the Pacific as well as in the other oceans. While the present sample shows no water in either of the two classes at 2·25 C between 33·7 and 33·9 per mille, probably because of the small sample size, waters of adjacent classes do appear in the diagram (Fig. 4b). From the vicinity of 2·5 C, 34·0 per mille a discernible ridge extends to 4·0 C, 34·35 per mille (about 80 cl t^{-1}) to join the extension of the main 75-per-cent boundary.

In the North Pacific distribution (Fig. 3b), Tropical Water forms a very distinct peak. Unlike their counterparts in the South Pacific distribution, the three classes in the 75-per-cent boundary stand clearly above their surroundings except along a line to the primary mode. Tropical Water is apparently an intrusion from the South Pacific. It does not seem to give rise to other waters occurring in important amounts except, possibly, mixtures with the Deep Water.

An Intermediate Water which is quite distinct from Tropical Water is found in the North Pacific. To indicate its analogy to Southern Intermediate Water, it will be called Northern Intermediate Water. It is associated with the widespread salinity minimum at depths ranging from 300 m to 800 m. The region covered by the minimum extends from the western side of the North Pacific to about 150°W. It lies between the surface waters of low salinity in the north and a line in the south running from 10°N at the western side of the Ocean to 20°N at 150°W. Most easily expressed in terms of potential specific volume and temperature, its range of characteristics is from 105 cl t^{-1} to 135 cl t^{-1} and from 5·0 C to 9·0 C.

Waters with these characteristics are not confined to the salinity minimum layer, but are also found farther east all the way to the American coast at depths ranging from 300 m to 600 m. The extension east of the minimum layer is bounded on the south by the parallel of 20°N. The northern boundary is more complex, extending eastward at 45°N to a point roughly 600 miles west of the American coast where it turns north to enclose a narrowing strip along the coast as far as Kodiak Island. Much of the Northern Intermediate Water of the extended region lies in the halocline layer between the surface layers of low salinity and the Deep Water. Some of the Northern Intermediate Water in the region of 150°W, but roughly 400 miles from the American coast, lies below a salinity minimum layer which is at smaller depths and higher potential specific volume anomalies than the more extensive salinity minimum associated with Northern Intermediate Water.

Northern Intermediate Water appears in the distribution (Fig. 3b) as an extension of the ridge from the principal mode to the vicinity of 5·0 C, 34·0 per mille. Near there the ridge is joined by a rather poorly defined limb of the distribution coming from the vicinity of 2·0 C, 33·3 per mile. At temperatures above those at the junction,

the main ridge changes direction to follow the 125 cl t^{-1} isostere. At 6·0 C, 34·0 per mille the ridge becomes quite distinct, but loses its distinctness beyond 7·0 C, and becomes almost indiscernible beyond 8·5 C.

The junction at 5·0 C, 34·0 per mille seems consistent with the idea that Northern Intermediate Water is formed in somewhat the same way as its southern counterpart. Water of characteristics near 2·0 C, 33·3 per mille descends from the surface and mixes with deeper, saltier waters reaching a smallest potential specific volume anomaly of 125 cl t^{-1}, possibly because of an increase in the rate of decrease of specific volume with depth.

The ridge from the principal mode to 5·0 C, 34·0 per mille represents the water beneath much of the Northern Intermediate Water, particularly in the northern part of the region where it is found. Along the southern edge of the region, Tropical Water lies under the Northern Intermediate Water. Between these two waters is a layer of transition represented in the distribution by an irregular region of higher volumes extending from 5·25 C, 34·55 per mille to the 120 cl t^{-1} isostere at salinities between 34·2 and 34·5 per mille.

Waters of the permanent thermocline layer. From the features representing Intermediate Waters in the distributions (Figs. 3b and 4b) ridges extend toward higher temperatures and salinities. These ridges represent the waters of the deeper portions of the permanent thermocline layers above the salinity minimum layers. In the entire Pacific there are two such groups of waters. One is composed of waters of the thermocline layer above the salinity minimum of the Southern Intermediate and Tropical Waters, the other of waters having the same relation to the Northern Intermediate Waters.

In the South Pacific distribution (Fig. 4b), where Tropical Water is merged with Southern Intermediate Water, the ridge corresponding to the waters of the permanent thermocline is rather broad. Starting from the largest classes along the 80 cl t^{-1} isostere, it runs to the vicinity of 34·75 per mille at 10·0 C (approximately 125 cl t^{-1}).

In the North Pacific distribution (Fig. 3b), both groups of thermocline waters are represented. One appears as an extension of the ridge through the detached 75-percent boundary to the vicinity of 34·65 per mille at 10·0 C (approximately 130 cl t^{-1}). This corresponds, of course, to the layer above Tropical Water and so is quite similar to the ridge of the South Pacific distribution, but not so broad nor so saline at 10·0 C. The other group of thermocline waters is represented in the distribution by a ridge from the vicinity of 6·0 C, 34·0 per mille to about 34·25 per mille at 10·0 C, that is, from the most conspicuous feature representing Northern Intermediate Water along a line nearly parallel to the first ridge.

Waters of the surface layers. The extremes of the distributions result for the most part from waters of the surface layers, the layers above the permanent thermocline or halocline. A notable exception is provided by the extreme characteristics of the Deep Water, which is evidently imported into the Pacific Ocean. The extremes of the North and South Pacific distributions (Figs. 3a and 4a) are much the same as those of the corresponding distributions of Pacific sea-surface characteristics given by COCHRANE (1956), although the latter show lower salinities occurring at all temperatures. The agreement between the two sets of distributions is very good in view of the facts that the 155 stations used in the present study represent a very small sample of surface characteristics and that seasonal changes are not taken into account.

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A notable feature of the distributions is the lack of low salinity water between 20 C and 24 C. In this range, there are no salinities below 33·5 per mille in the North Pacific distribution (Fig. 3a) or below 34·5 per mille in the South Pacific distribution (Fig. 4a). This situation arises from the considerable excess of evaporation over precipitation in the regions where temperatures of 20 C to 24 C are found at the sea-surface.

The *univariate distributions.* Means and certain percentiles for the univariate distributions are listed in Table 3. These statistics are based on the fine-scale distributions.

The gigantic mode of the bivariate distributions (1·25 C or 1·75 C, 34·65 per mille, 35 cl t^{-1}) determines the location of the primary modes in all the univariate distributions (Figs. 2b, 3b, and 4b, Table 2). The secondary mode (4·25 C, 34·55 per mille, 65 cl t^{-1}) results in the modes in the potential temperature and potential specific volume anomaly distributions, but not in the salinity distributions because its salinity, 34·55 per mille, lies so close to that of the primary mode.

Table 3. *Means and percentiles*

Portion of Pacific Ocean	*Mean*	5%	25%	50%	75%	95%
			Potential temperature, C			
Entire	3·36	0·77	1·33	1·91	3·45	11·09
North	3·38	1·03	1·30	1·81	3·27	11·60
South	3·36	0·53	1·40	1·99	3·73	10·10
			Salinity, per mille			
Entire	34·62	34·27	34·57	34·65	34·70	34·79
North	34·59	34·16	34·55	34·64	34·69	34·78
South	34·64	34·33	34·57	34·65	34·72	34·80
			Potential specific volume anomaly, cl t^{-1}			
Entire	62	22	31	39	66	162
North	64	24	32	39	64	186
South	59	22	30	40	68	138

All of the potential temperature distributions (shown at the bottom of each diagram) are quite skew and peaked because of the primary mode. A mode centred at about 27 C in all the coarse distributions represents the large quantities of surface water near this temperature. The Pacific Ocean has a smaller proportion of water at both temperature extremes than other oceans, as is shown by MONTGOMERY (1958, Table 3). The North Pacific is particularly deficient at low temperatures and the South Pacific at high temperatures, as the 5 and 95 percentiles clearly indicate. In spite of the lower temperature of the mode and median of the North Pacific, its mean temperature is higher than that of the South Pacific. This results from the larger proportion of quite high temperatures in the North Pacific.

It is well known that the North and South Pacific differ considerably in their salinity ranges. Because of this difference and the fact that the two parts of the Pacific have their primary modes at the same salinity, the distribution for the North is very skew while that for the South is not.

The distributions of potential specific volume anomaly are all very skew. The modal class for the South Pacific is located at 25 cl t^{-1}, although nearly as much

lies in the class centred at 35 cl t^{-1}, the class corresponding strictly to the primary bivariate mode. Because of its low salinities coupled with high temperatures, the North Pacific has a considerably longer tail to high specific volumes than has the South. In addition to the primary and secondary modes discussed above, the distributions all have modes at 105 cl t^{-1}. While such a small mode must be viewed with some scepticism, its occurrence in both the North and South distributions lends support to its reality.

Conclusion. The information presented above, it is believed, is a necessary step toward classifying Pacific waters systematically and putting studies of their evolution, maintenance, and modification on a quantitative basis. The information also seems essential to investigating the general circulation of the Pacific, particularly the deep circulation. The frequency distributions obtained are, as has been pointed out, only first approximations. Accurate representation of the larger features has been sought. For the North Pacific, this aim seems to have been attained. For the South Pacific, however, there may well be distortion of even some major features because of the tremendous volumes in the central South Pacific for which no serial data are now available. Seasonal changes and smaller permanent features of the geographical distribution have been neglected. These matters, while perhaps vitally important in the evolution of certain waters, can probably be approached best by a route other than the one followed in the present study. Basic information still lacking in the study of Pacific water characteristics is a uniform charting of the geographical distribution of characteristics for the entire Pacific. The frequency distributions presented above should prove valuable in deciding how such charting can best be carried out.

Acknowledgement—The writer wishes to record his gratitude to Dr. R. B. MONTGOMERY for suggestions on many points in this paper.

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Contribution from the Department of Oceanography and Meteorology of the Agricultural and Mechanical College of Texas, Oceanography and Meteorology Series No. 115, *based on investigations conducted for the Texas A & M Research Foundation through sponsorship of the Office of Naval Research Contract N7 onr-48702.*

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Frequency distribution of potential temperatures and salinities in the Indian Ocean

M. J. POLLAK

(*Received* 30 *September* 1957)

Abstract—A correlation table of potential temperatures and salinities for the entire volume of the Indian Ocean is presented. Frequencies, in terms of 10^4 km^3, are given for class intervals of 0·5° C × 0·1 per mille. Three classes, in the temperature range 0·5 to 2·0° C and salinity range 34·7 to 34·8 per mille, include 32 per cent of the total volume. This group represents the core of the deep water of the Indian Ocean. In the central portion of the ocean, and in the Arabian Sea and Bay of Bengal, only very limited station data are available. Consequently, the correlation table represents a substantial amount of subjective interpolation.

INTRODUCTION

THE identification of ocean waters by their temperature-salinity correlation has long been a standard technique in oceanography. Most commonly, *in situ* temperatures, T, have been used for this purpose, rather than the more significant potential temperatures, θ, in which the effect of pressure has been eliminated.

But, to date, very little work has been done to determine the volumes of water represented by the various θ-S types, especially on an ocean-wide basis. A quantitative inventory of water characteristics is virtually a prerequisite to the development of a valid theory of oceanic circulation.

The present paper represents such an inventory of the Indian Ocean. Together with parallel studies of the Atlantic and Pacific Oceans by MONTGOMERY and COCHRANE respectively, it should help to eliminate a substantial gap in descriptive oceanography. The results for the Indian Ocean must be considered preliminary in nature because of the inadequacy of the data ; large areas in the central and northern sectors of this ocean are almost completely devoid of serial observations.

METHODS

The volume of the Indian Ocean, including the Red Sea, Persian Gulf, and Andaman Sea, is 29,195 × 10^4 km^3 according to KOSSINNA (1921), with a surface area of about 75 × 10^6 km^2. In order to obtain results that would be comparable with those for the other two oceans, a sampling network of one station per 10^6 km^2 of surface area was selected. In the region south of latitude 50°S and along the east coast of Africa, the outstanding series of data obtained by the *R.R.S. Discovery* in the course of 20 years would have permitted a denser network of stations. On the other hand, in the large unsampled areas already mentioned, even the minimum number of stations was unobtainable.

First, as many stations as possible were selected on the basis of reasonably uniform horizontal spacing and maximum depth of sampling. These are the primary stations shown in Fig. 1. Wherever an otherwise unused deeper station was located in the

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vicinity of a primary station, provided no shallow ridge intervened, its additional sampling depths were appended to the primary series. These secondary deep stations are also indicated on the chart. This procedure yielded 66½ primary stations, with the half station referring to the one in the Red Sea. Because of the small volume and shallow sill depth of this sea, its station was weighted only one half.

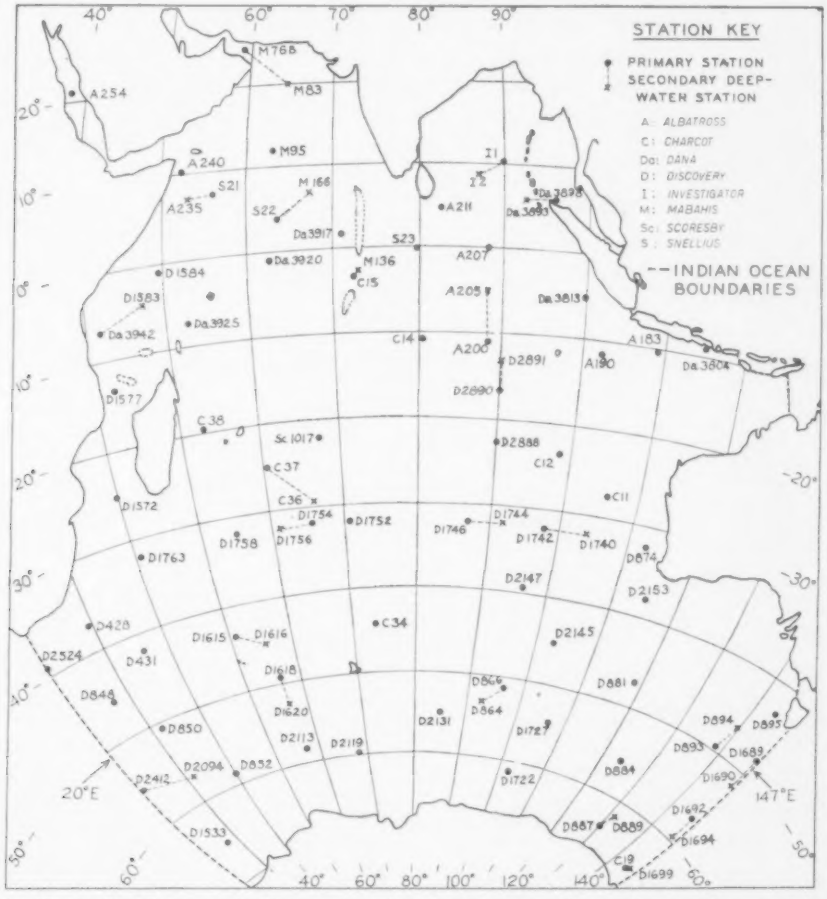

Fig. 1. The Indian Ocean and adjacent seas, showing primary and secondary stations used in this study.

To compensate for the horizontal gaps in the data it was assumed that any missing station could be represented by mean values of the nearest surrounding stations. This averaging was accomplished by giving additional weight to the adjacent data. Even this process was unsatisfactory in some instances, especially in the Bay of Bengal, where one station had to be given a weight of 2½. However, no alternative was possible.

Vertically, each observation was weighted according to the half-distances to the next higher and lower sampling depths. Ten metres was taken as unit weight. With 10^6 km^2 as the area unit, the volumetric unit thus becomes 10^4 km^3. When con-

sidered in the light of the total volume of the Indian Ocean and the limited number of observations available, the magnitude of the unit volume does not appear unduly large.

One additional adjustment to the weight of each observation was required. This correction factor was based on the average area enclosed by each depth zone, for instance 1000-2000 m, and on the number of stations providing observations in this zone. In the case of the deepest observation at a station, the depth to the bottom was also taken into account. The adjustment was made by 10° zones of latitude, a convenient form of subdivision used by KOSSINNA. After this final processing, the sum of all weights equalled the total volume of the Indian Ocean.

For 66½ stations, the average weight per station is 439 units of volume. But, as a result of their irregular geographical distribution and different depths attained, the station weights varied widely. The largest weight was 1213 units, or slightly over 4 per cent of the total, assigned to *Discovery* Station 2888 near the centre of the Indian Ocean. This station included the individual observation with the greatest weight, 369 units at a depth of 3950 m.

The basic θ-S class covered the ranges 0·5 °C by 0·1 per mille. The weights of all observations in each class were summed, thus giving the frequency of that class in terms of 10^4 km^3. The distribution of these frequencies is shown in Fig. 2.

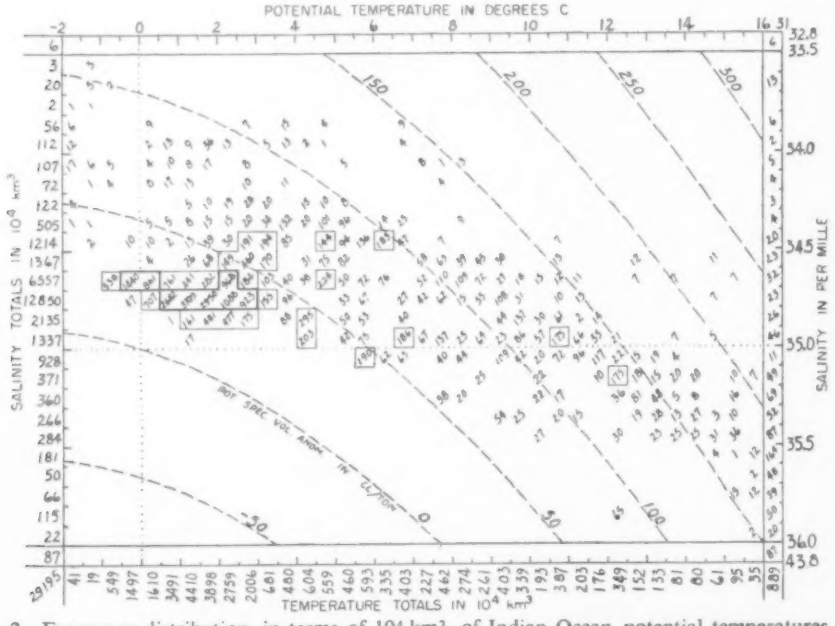

Fig. 2. Frequency distribution, in terms of 10^4 km^3, of Indian Ocean potential temperatures and salinities by classes of 0·5° C × 0·1 per mille. Heavy class boundaries include 50 per cent and light class boundaries 75 per cent of the total volume. High temperature classes, compressed in the marginal band, comprise 3 per cent of the volume.

In order to retain practical limits to this correlation table, the observations at potential temperatures above 16°C, comprising only 3 per cent of the total volume, have been summarized in the margin.

The 50 per cent and 75 per cent boundaries were established by the cumulative addition of frequencies in descending order of magnitude. The discontinuity of the 75 per cent boundary, as well as the discontinuity of the data in general (as exemplified by scattered classes with no observations), may be attributed to the crude sampling method employed. The question whether these discontinuities are real or fictitious will be resolved only after the establishment of a far more comprehensive network of serial observations than is now extant.

DISCUSSION

Especially noteworthy is the small number of classes (8) within the 50 per cent boundary. Each of these contains between 3 and 13 per cent of the volume. The three largest ones alone, in the ranges 0·5 to 2·0°C and 34·7 to 34·8 per mille, include

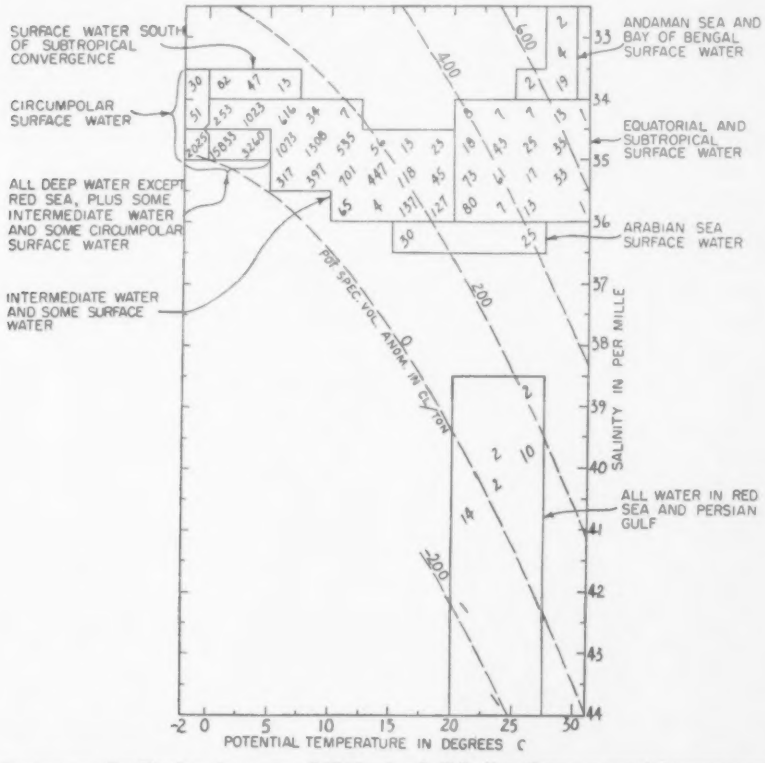
SURFACE WATER SOUTH OF SUBTROPICAL CONVERGENCE
CIRCUMPOLAR SURFACE WATER
ALL DEEP WATER EXCEPT RED SEA, PLUS SOME INTERMEDIATE WATER AND SOME CIRCUMPOLAR SURFACE WATER
INTERMEDIATE WATER AND SOME SURFACE WATER
ANDAMAN SEA AND BAY OF BENGAL SURFACE WATER
EQUATORIAL AND SUBTROPICAL SURFACE WATER
ARABIAN SEA SURFACE WATER
ALL WATER IN RED SEA AND PERSIAN GULF
FOR SPEC. VOL. ANOM. IN CL/TON
SALINITY IN PER MILLE
POTENTIAL TEMPERATURE IN DEGREES C

Fig. 3. Frequency distribution, in terms of 10^4 km^3, of all Indian Ocean potential temperatures and salinities by classes of 2·5° C × 0·5 per mille. Boundaries demarcate the various types of water found. Surface, intermediate, and deep water are here defined, respectively, as the water between the sea surface and 200 m, between 200 and 1,500 m, and below 1,500 m.

nearly one third of the total volume and comprise the core of the deep water of the Indian Ocean. A secondary frequency maximum, much smaller in magnitude, occurs at slightly lower potential temperature and lower salinity but at approximately the same potential specific-volume anomaly as the primary maximum. A detailed

station-by-station analysis of the deep water, to determine if it is all of the same origin, is beyond the scope of the present study. However, a cursory inspection of the data suggests that the deep water originates in the circumpolar regions, though not necessarily formed in the Indian Ocean sector of the Antarctic waters. In this regard it should be remembered that the data used were obtained over a period of many years and that there is no reason to expect bottom water of identical characteristics to be formed year after year. Also worthy of mention is the finding, in the single θ-S class of maximum frequency, of observations separated by as much as 66° of latitude (e.g. *Albatross* Station 240 and *Discovery* Station 884).

In Fig. 3 the entire potential temperature and salinity range of the Indian Ocean is covered in classes of 2·5°C by 0·5 per mille. The Table brings out clearly the relative isolation of the highly saline waters of the Red Sea and the Persian Gulf. Also to be noted are the wide temperature and salinity ranges of the 200 m surface layer in the equatorial and subtropical expanses of the ocean. This feature brings up an additional weakness in the data. The relationship of the surface layer to the subsurface waters cannot be fully established without a reasonably complete observational coverage of the ocean both in winter and summer. Because of the paucity of stations, the present study included data from all seasons indiscriminately. Since the upper 200 m contain only 5 per cent of the total volume, this merging of all seasons does not do undue violence to the statistical results in their present preliminary form.

As has already been suggested, the frequency distribution of potential temperatures and salinities in the Indian Ocean can be made more detailed and reliable only after a major increase in observational data has been accomplished.

An interesting by-product of this study is the determination of average values of potential temperature and salinity for the entire Indian Ocean. These means, derived from the original tabulation of the data by intervals of 0·5°C and 0·1 per mille, are 3·72°C and 34·76 per mille. Their probable errors are not evaluated.

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Contribution No. 34 *from the Chesapeake Bay Institute. This investigation was supported in part by the Geophysics Branch of the Office of Naval Research.*

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Water characteristics of Atlantic Ocean and of world ocean*

R. B. MONTGOMERY

(*Received* 5 *February* 1958)

Abstract—The volume of Atlantic Ocean water in each bivariate class with potential-temperature range of 0·5 C and salinity range of 0·1 per mille has been estimated from 105 uniformly distributed hydrographic stations. The resulting statistics are presented on a pair of characteristic diagrams, each having potential temperature and salinity as co-ordinates, potential specific-volume anomaly being represented by isopleths. Several water types stand out distinctly as separate modes. These statistics are then combined with COCHRANE's for the Pacific Ocean and POLLAK's for the Indian Ocean to form a pair of diagrams for the world ocean. These diagrams provide the first ocean-wide frequency distributions of water characteristics. It is found that the mean potential temperature is 3·52 C, the mean salinity is 34·72 per mille, and the mean potential specific-volume anomaly is 56 cl/ton ; these values accord with the mean temperature and salinity estimated by KRÜMMEL in 1907.

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INTRODUCTION

THE correlation of temperature and salinity, two conservative characteristics of sea water, was first put on a systematic basis when HELLAND-HANSEN (1916) introduced the temperature-salinity diagram. This diagram led the way for all the characteristic diagrams that have come to be regarded as valuable analytical tools in both oceanography and meteorology.

Characteristic diagrams are commonly used in what amounts to qualitative analysis, in that points or lines represent kinds of water or air. The present study, however, is one of a series using characteristic diagrams in quantitative analysis to show bivariate frequency distribution. In this series, bivariate distributions for sea water have been prepared for a point by MONTGOMERY (1955), for a surface by COCHRANE (1956), and for volumes in the present group of three papers. The first two papers of this group are by COCHRANE (1958) and POLLAK (1958).

The purpose of these three papers is to furnish some basic sea-water statistics showing how much there is of each kind according to temperature-salinity correlation. As the water at all depths is treated together, actual temperature is not sufficiently conservative, so these papers consistently employ potential temperature, computed for each sample by use of graphs based on calculations by HELLAND-HANSEN (1930).

The results are shown on diagrams with potential temperature and salinity as co-ordinates, like the diagrams of WÜST (1933). The orientation of the present diagrams, which have (potential) temperature as abscissa and negative salinity as ordinate, results by rotating the usual temperature-salinity diagram through 90°. The present orientation is advantageous for plotting station curves, all the other variables being plotted against a common temperature scale as abscissa (MONTGOMERY, 1954). Isopleths of potential specific volume, rather than potential

*Presented in preliminary form at Symposium on Abyssal Circulation (International Association of Physical Oceanography, International Union of Geodesy and Geophysics), Toronto, 5-6 September 1957.

density, are drawn on the diagrams for reasons explained by MONTGOMERY and WOOSTER (1954).

The accuracy is limited to a first approximation, intended to show the major features reliably. The methods adopted are adequate for this limited goal, and no attempt is made to utilize all available data.

This third paper of the group is composed of two parts. The first part presents the statistics for the Atlantic Ocean. The second part combines COCHRANE's statistics for the Pacific Ocean and POLLAK's for the Indian Ocean with the Atlantic statistics to obtain statistics for the world ocean.

ATLANTIC OCEAN

Method

The volume treated is the entire Atlantic Ocean and includes all tributary seas, such as the Central American seas, the Arctic Sea and other northern seas, and the Mediterranean Sea and Black Sea. South of Africa the boundary separating the Indian Ocean is the meridian 20°E. The boundary across Drake Passage separating the Pacific Ocean runs between Cape Horn and King George Island. With similar definitions of the Pacific and Indian oceans, the three together comprise the world ocean, which contains all sea water.

The data chosen consist of the 105 stations listed in Table 1 and mapped in Fig. 1. They are seen to be distributed rather uniformly. The surface area of the Atlantic Ocean is $106{\cdot}2 \times 10^6$ km² (STOCKS, 1938, Tab. 35), so each station represents an area of about 10^6 km². Wherever possible, stations are chosen that have no greater gaps than 500 m between samples or between the lowest sample and the sea bottom.

It was decided to adhere to values of potential temperature and salinity for actual samples, thus avoiding all spacial and temporal interpolation of water characteristics.

Because the samples are not uniformly spaced in the vertical, each sample is weighted in proportion to the thickness of the layer represented. The layer is bounded by midpoints between samples or by the sea surface or sea bottom as the case may be. The volume assigned to each sample is the layer thickness to nearest decametre (10 m) times 10^6 km², the horizontal area. The volume for each sample, therefore, is an integer (the weight or number of decametres) times the volume unit 10^4 km³. For example, a sample spaced 500 m from the next higher and next lower samples is assigned the volume 50×10^4 km³.

This primary weighting resulted in a total Atlantic Ocean volume considerably exceeding the actual volume, the discrepancy being due to deliberate selection of the deepest stations available. The weights have then been reduced, where appropriate, so as to yield the correct volume of each tributary sea and of each 10° zone of the entire Atlantic (STOCKS, 1938, Tab. 38, 39).

All samples at each station are used, including samples in the surface layer. Although the surface layer is subject to seasonal changes, in this first approximation no effort is made to choose stations distributed throughout the year or to allow otherwise for seasonal effects.

For the 105 stations there are 2,089 samples. The volumes assigned to samples range from 1×10^4 km³ to 133×10^4 km³, but very few exceed 75×10^4 km³. The total volume is $35{,}283 \times 10^4$ km³. Except for this total volume, all volumes presented

are accurate to no better than a few per cent. The insignificant digits are retained only for simplicity in accounting.

To facilitate sorting the data, each sample has been entered on a card, which shows depth, potential temperature, salinity, and volume and is identified as to station,

Table 1. *List of stations in Atlantic Ocean*

Abbr.	*Vessel*	*Stations*	*No.*	*Year*	*Months*	*Source*
A	*Altair*	1, 2, 14, 46, 99	5	1938	V-VII	*Bull. hydrogr., Copenh.*
At	*Atlantis*	1035	1	1931	VIII	*Bull. hydrogr., Copenh.,App.*
		1504, 1524, 1581	3	1933	III-IV	*Bull. hydrogr., Copenh.*
		2003	1	1934	III	*Bull. hydrogr., Copenh.*
		2413	1	1935	IV	*Bull. hydrogr., Copenh.*
		2537	1	1936	III	*Bull. hydrogr., Copenh.*, 1940-46, App.
		2871	1	1937	VI	*Bull. hydrogr., Copenh.*, 1940-46, App.
		3740	1	1940	I	*Bull. hydrogr., Copenh.*
		4541, 4588	2	1947	IV-VI	*Bull. hydrogr., Copenh.*
		4726	1	1948	V	*Bull. hydrogr., Copenh.*
		5002, 5066-5068	4	1952	VIII-XII	*Bull. hydrogr., Copenh.*
		5209, 5212	2	1954	XI	Kindness L. V. Worthington
		5358	1	1955	VII	Kindness L. V. Worthington
Cg	*Carnegie*	14, 19	2	1928	VIII	Fleming *et al* (1945)
D	*Deutschland*	55	1	1911	XII	Brennecke (1921)
		57	1	1912	I	Brennecke (1921)
Da	*Dana*	4070	1	1930	V	*Dana-Report*, **12**, 1937
		4447	1	1932	VII	*Bull. hydrogr., Copenh.*
		5142	1	1934	V	*Bull. hydrogr., Copenh.*
		6621	1	1947	VI	*Bull. hydrogr., Copenh.*
		6814	1	1948	V	*Bull. hydrogr., Copenh.*
		8337	1	1952	VII	*Bull. hydrogr., Copenh.*
Di	*Discovery II*	1515	1	1935	II	*Discovery Rep.*, **22**, 1942
		1996	1	1937	III	*Discovery Rep.*, **24**, 1944
	Gjøa	3	1	1901	IV	Nansen (1906)
GS	*G. O. Sars*	119, 222, 230	3	1952	III-VI	*Bull. hygrogr., Copenh.*
IP	*General Greene*	1287	1	1931	VII	Smith *et al.* (1937)
IP	*Evergreen*	3702, 3714	2	1948	VII	Soule *et al.* (1950)
	Johan Hjort	165	1	1952	IV	*Bull. hydrogr., Copenh.*
	Maud	14	1	1922	IX	Sverdrup (1929)
M	*Meteor*	9-90	20	1925	VI-XII	Wüst (1932)
		116-243	21	1926	I-XII	Wüst (1932)
		247-306	10	1927	I-V	Wüst (1932)
		127	1	1935	III	*Bull. hydrogr., Copenh.*
Na	*Nautilus*	2	1	1931	VIII	Sverdrup (1933)
N-169	*SSSR-N*-169 (Soviet airplane)		1	1941	IV	Chernigovsky (1943)
NPI	North Pole I (Soviet drifting station)		1	1937-8		Shtokman (1943), see also Shirshov (1938)
	Project Skijump	3	1	1951	V	Worthington (1953)
		4	1	1952	III	Worthington (1953)
T-3	Ice Island T-3	7	1	1953	VII	Unpublished manuscript by L. V. Worthington, Woods Hole Oceanogr. Inst. ref. no. 53-92
	(Black Sea)		1	Average values reproduced by Neumann (1943), pp. 4, 10)		
	(Hudson Bay)	35	1	1930	VIII	Hachey (1932)
		Total stations	105			

month, year, and position. The cards are sorted into temperature classes of range 0·5 C, and each of these classes is subdivided into salinity classes of range 0·1 per

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mille. The volume of water in each bivariate class 0·5 C × 0·1 per mille is found by summation.

These fine-scale classes, 0·5 C × 0·1 per mille, are too small for convenient representation of the entire range of occurrences, so the bivariate distribution is presented

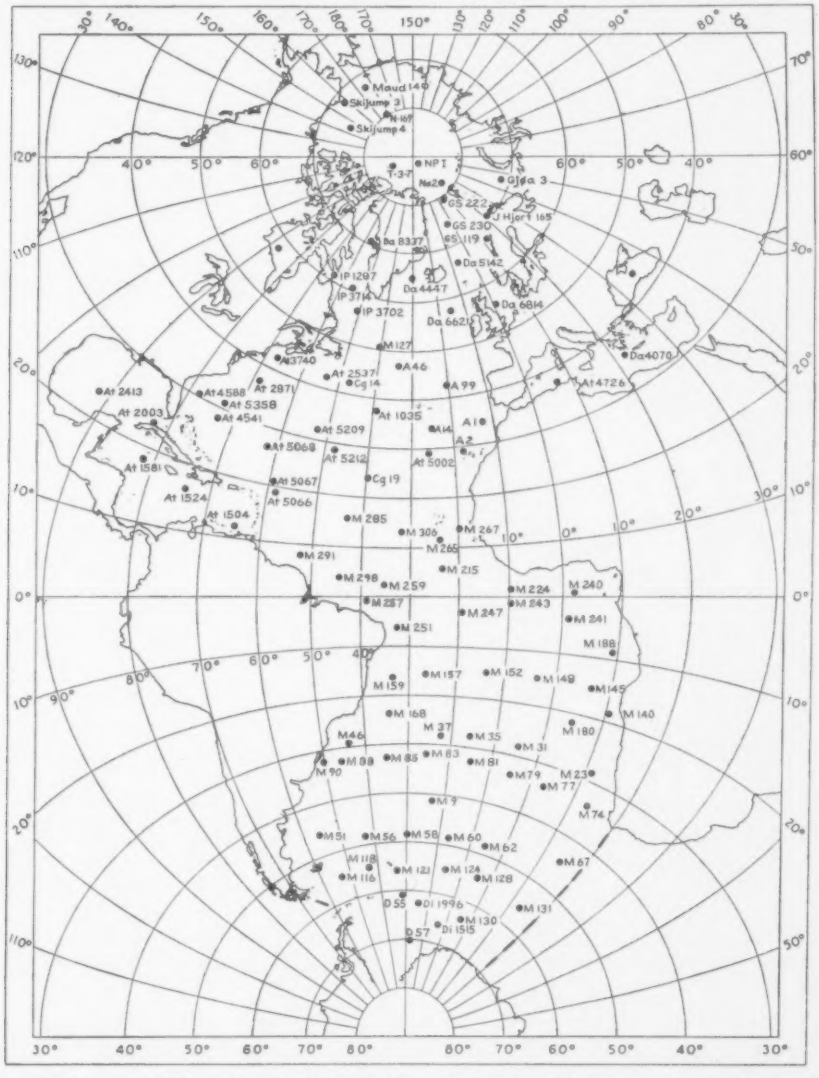

Fig. 1. Positions of 105 stations in Atlantic Ocean (transverse Mercator projection). A, *Altair* ; At, *Atlantis* ; Cg, *Carnegie* ; D, *Deutschland* ; Da, *Dana* ; Di, *Discovery II* ; GS, *G. O. Sars* ; IP, International Ice Patrol ; M, *Meteor* ; Na, *Nautilus* ; N-169, *SSSR-N-169* ; NPI, North Pole I ; T-3, Ice Island T-3.

on two scales. The entire range is represented in Fig. 2 by coarse-scale classes measuring 2 C × 1 per mille. The densely populated area of this diagram is represented in detail in Fig. 3 by fine-scale classes.

Each coarse-scale class is composed of 40 fine-scale classes. The fine-scale classes are uniform throughout the present group of three papers, and the same classes were used by MONTGOMERY (1955). The coarse-scale class, necessarily large because of the large range of salinity in the Atlantic Ocean, has an area 2 C per mille, which contrasts with 0·8 C per mille for the previous COCHRANE (1956) class, 1 C per mille for the present coarse-scale COCHRANE class, and 1·25 C per mille for the present coarse-scale POLLAK class. These differences need to be borne in mind in comparing the coarse-scale diagrams of the several papers.

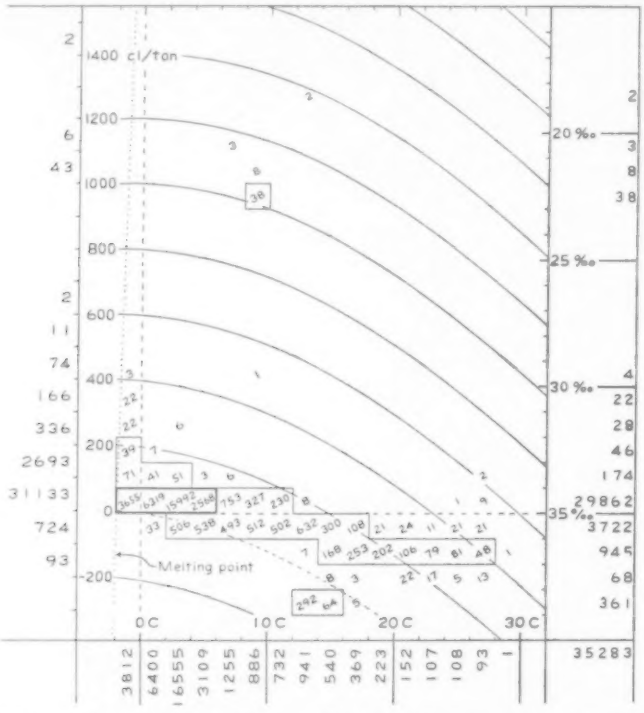

Fig. 2. Atlantic Ocean on coarse-scale diagram of potential temperature against salinity. Potential specific-volume anomaly is represented by curves. Oblique numbers give 10^4 km^3 of water in each bivariate class 2 C × 1 per mille. Heavy boundary encloses 75 per cent of water (classes with 2568 × 10^4 km^3 or more), fine boundary encloses 99 per cent (38 × 10^4 km^3 or more). Sums at bottom give the distribution by potential temperature, at right by salinity, and at left by potential specific-volume anomaly.

In both diagrams (Figs. 2, 3) the classes are represented by squares, so the relative scale is different : 1 per mille of salinity is represented by the same length as 2 C on the coarse scale but as 5 C on the fine scale.

On a bivariate distribution like Fig. 2 or 3, a boundary can be drawn to enclose all classes of a certain frequency (volume) and greater frequency. The possible boundaries thus defined form a series composed of the different frequencies on the diagram (in Fig. 2 there are 44 different frequencies : 15,992, 6,319, . . . 1). It is desirable to select from this series a few standard boundaries such that each encloses a standard proportion of occurrences. In other words, each standard boundary encloses the smallest area that contains at least the stated proportion of occurrences. The coarse-scale diagram (Fig. 2) shows the 75-per-cent and 99-per-cent boundaries; the fine-scale diagram (Fig. 3) shows the 50-per-cent and 75-per-cent boundaries.

In all the blank classes on the diagrams the volume is 0. Classes outside the range of the fine-scale diagram (Fig. 3) are summed by potential temperature or salinity and are entered as (oblique) numbers in the bordering band.

On each diagram the univariate distribution of potential temperature is shown by sums at the bottom, of salinity at the right, and of potential specific-volume anomaly

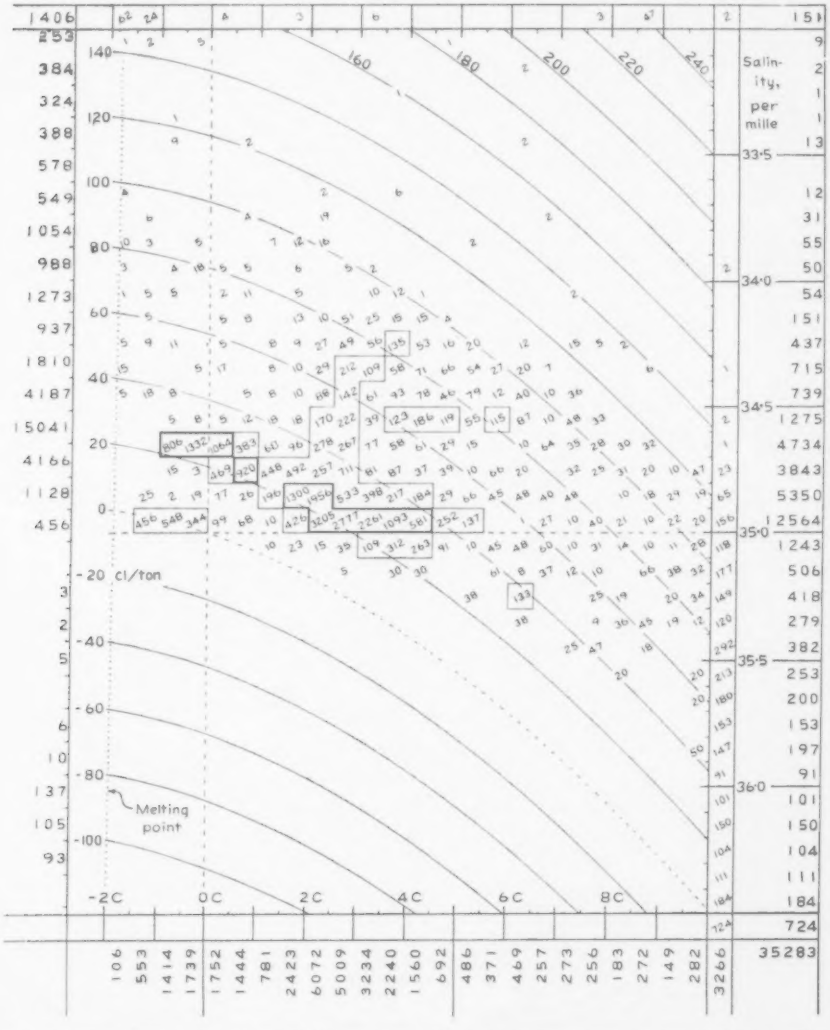

Fig. 3. Atlantic Ocean on fine-scale diagram of potential temperature against salinity. Potential specific-volume anomaly is represented by curves. Oblique numbers give 10^4 km^3 of water in each bivariate class 0·5 C × 0·1 per mille. Water outside the range of the diagram is represented by oblique numbers in bordering band and amounts to 3587 × 10^4 km^3 or 10 per cent of total. Heavy boundary encloses 50 per cent of total (classes with 581 × 10^4 km^3 or more), fine boundary encloses 75 per cent (109 × 10^4 km^3 or more). Sums at bottom give the distribution by potential temperature, at right by salinity, and at left by potential specific-volume anomaly.

at the left. (The sums include classes outside the fine-scale diagram.) The sum given

for each interval of potential specific-volume anomaly is the sum for all fine-scale bivariate classes having centres within the interval.

Discussion

The spottiness of the diagrams is partly significant and partly fictitious, the result of limited sampling. The aim of the discussion is to point out some of the significant features on the diagrams.

It is interesting to map the water in each class, and the map is easily prepared from the cards. A number of such maps have helped in the preparation of the following comments. None of the maps are reproduced, although they would be essential for a really adequate discussion.

Distinctive water is found in several tributary seas.

Black Sea. On the coarse-scale diagram (Fig. 2) the 4 classes with salinity less than 23 per mille contain all the Black Sea water and none other. The mode for this water is at 9 C, 22·5 per mille, 1,050 cl/ton*. The last two values show up as subordinate modes in the univariate distributions of salinity and of potential specific-volume anomaly.

Mediterranean Sea. At the other extreme, the 5 classes with salinity greater than 37 per mille and temperature between 12 C and 18 C contain all the Mediterranean water and none other. (In summer, of course, there are temperatures higher than 18 C). The mode is at 13 C, 38·5 per mille. These values show up as the secondary modes in the univariate distributions of potential temperature and of salinity on this diagram, and a subordinate mode in potential specific-volume anomaly shows up at − 85 cl/ton on the fine-scale diagram (Fig. 3). The Mediterranean Sea contains the water of lowest potential specific volume in the Atlantic Ocean, and still lower values occur only in the Red Sea of the Indian Ocean.

Arctic and Greenland-Norwegian seas. These seas contain the water within the cold, salty high (high-frequency area) on the fine-scale diagram. The mode is at − 1 C, 34·95 per mille, 0 cl/ton. The core of this water, roughly the 3 classes enclosed by the 75-per-cent boundary, is known as Arctic Deep Water (SVERDRUP *et al.* 1942, p. 658). Potentially heavier water occurs nowhere in the ocean except in the Mediterranean Sea and Red Sea. Actually the Arctic and Greenland-Norwegian seas contain all the water (1,780 × 10^4 km³) colder and saltier than 34·7 per mille at 0·0 C, than 34·8 per mille at 1·0 C, than 34·9 per mille at 1·5 C, and than 35·0 per mille at 3·0 C†.

One striking feature of the fine-scale diagram is the bimodal distribution brought out by the 50-per-cent boundary. The primary mode, at 2·25 C, 34·95 per mille, 20 cl/ton, represents North Atlantic Deep Water. The secondary mode, at 0 C, 34·65 per mille, 25 cl/ton, represents water in the South Atlantic. The two modes are repeated in the univariate distributions of potential temperature and salinity but merge to form the sharp primary mode in the distribution of potential specific-volume anomaly (25 cl/ton).

*This short expression stands for potential temperature 9 degrees centigrade, salinity 22·5 per mille (parts per thousand), potential specific-volume anomaly 1,050 centilitres per ton (metric).

†TAIT (1957, p. 77) draws attention to sporadic observations of " heavy oceanic water ", colder than 0 C and saltier than 35 per mille, in the Faroe-Shetland Channel (Norwegian Sea) at depths of about 1,000 m. The salinity ranges as high as 35·35 per mille, potential specific-volume anomaly as low as − 30 cl/ton. The volume of sub-zero water saltier than 35 per mille, however, seems to be of the order of only 100 m × 10 km × 100 km = 100 km³.

The broad extent of the North Atlantic Deep Water is well illustrated by the modal class, which contains $3{,}205 \times 10^4$ km^3 composed of 71 samples from 42 stations. The samples are distributed in latitude from 60°N to 30°S and in depth from 2,500 m to 5,000 m (and at 100 m in the Norwegian Sea). Of all the water from 1·5 C to 10·0 C at this salinity (34·9 to 35·0 per mille) and from 3 C to 10 C with salinity exceeding 35 per mille, the total being $12{,}876 \times 10^4$ km^3, most lies north of the equator ; the rest lies in the northern half of the South Atlantic and is of North Atlantic origin.

The secondary high includes the Antarctic Bottom Water. According to WÜST (1933, p. 54) the extreme bottom water in the Weddell Sea is typically at — 0·9 C, 34·67 per mille, 21 cl/ton. This secondary high merges with POLLAK's Indian Ocean high, which in turn merges with the Pacific Ocean high found by COCHRANE. If all Atlantic classes from — 1 C to 3 C at salinity 34·6 to 34·7 per mille and from 0 C to 3 C at 34·7 to 34·8 per mille are grouped together, the volume is $7{,}591 \times 10^4$ km^3, and all this water lies in the South Atlantic except for a bit in the upper 300 m of the Arctic Sea. The same group of classes includes all Indian and Pacific water within the respective 50-per-cent boundaries.

The small mode at 2·25 C, 33·8 per mille, 105 cl/ton is composed of the water that, according to SVERDRUP (1957, p. 643), sinks at the Antarctic Convergence and mixes with saltier water to form Antarctic Intermediate Water. The indistinct frequency ridge extending from this point through 4·25 C at 34·35 per mille represents the core of the tongue of Antarctic Intermediate Water in the South Atlantic. Actually, all the water with characteristics between 2 C and 4 C and between 33·6 and 34·7 per mille, with minor exception, lies in the South Atlantic. This water includes not only Antarctic Intermediate Water (salinity minimum) but also underlying water down to the North Atlantic Deep Water (salinity maximum).

The methods used in preparing the diagram are too rough to resolve this part of it clearly. For instance, the mode indicated where the 75-per-cent boundary surrounds the high from 3·5 C to 5·0 C at 34·5 to 34·6 per mille may be fictitious. This area represents water that, with minor exception, is limited to the zone between 22°S and 8°N and to depths between 700 m and 1,000 m and is found at or below the salinity minimum. This tropical type of water is of interest if a more thorough study substantiates the reality of the mode, especially because COCHRANE finds a stronger mode at almost exactly the same position on the Pacific Ocean diagram.

A striking feature of the fine-scale diagram for each ocean is the sharp frequency gradient on at least one side of each dominant mode. In Fig. 3, for example, the modal class at each of the three highest modes contains a volume at least 200 times the volume in an adjacent class. The most prevalent water types, therefore, are sharply defined in at least one direction on the bivariate distribution.

The three oceans may be compared with regard to the number of classes enclosed by the boundaries drawn on the fine-scale diagrams :

	50 per cent	*75 per cent*
Pacific Ocean (COCHRANE)	5	20
Indian Ocean (POLLAK)	8	33
Atlantic Ocean (Fig. 3)	11	44
World ocean (Fig. 5)	12	43

It is seen that the Pacific is the most homogeneous, the Atlantic the most heterogeneous.

In the univariate distribution of potential temperature at the bottom of the diagrams the primary mode, 2·25 C, is due to North Atlantic Deep Water. The secondary mode, 0 C, represents water in the South Atlantic Ocean. These two modes straddle the primary modes for the Pacific and Indian oceans, both 1·25 C. The subordinate mode due to the Mediterranean Sea is at 13 C. The amount of water potentially colder than 0 C is greatest in the Atlantic Ocean (Atlantic 3,812, Indian 2,106, Pacific 489 $\times$ 10^4 km^3). It may be seen from Table 2 in the next section that for the Atlantic Ocean the mean potential temperature is 3·73 C, the median 2·6 C ; half the water falls between the quartiles 1·7 C and 3·9 C, nine tenths between the 5-percentiles $-$ 0·6 C and 13·7 C.

In the salinity distribution at the right of the diagrams the primary mode, 34·95 per mille, is due to North Atlantic Deep Water. The secondary mode, 34·65 per mille, represents water in the South Atlantic Ocean and coincides with the primary mode for the Pacific Ocean. (The primary mode for the Indian Ocean, 34·75 per mille, is intermediate.) There are subordinate modes at 38·5 per mille (Mediterranean Sea) and 22·5 per mille (Black Sea). The mean and median salinities are both 34·90 per mille ; half the water falls between 34·71 and 34·97 per mille, nine tenths between 34·41 and 35·73 per mille.

The distribution of potential specific-volume anomaly is shown at the left of the diagrams. The primary mode is at 25 cl/ton, the modal class containing no less than 42 per cent of the Atlantic Ocean. There are subordinate modes at $-$ 85 cl/ton (Mediterranean Sea) and 1,050 cl/ton (Black Sea). The mean is 45 cl/ton, and the median is 28 cl/ton ; half the water falls between 22 and 46 cl/ton, nine tenths between 8 and 137 cl/ton.

The results obtained by this first approximation should in themselves prove useful in a variety of ways, especially as background statistics in studies relating to geographical distributions of characteristics and to circulation. Data from the Atlantic Ocean are available, however, for a closer network in space and time. It would be feasible to reach a better approximation by means of a more thorough analysis, and smaller features would be reliably revealed.

COMBINED STATISTICS FOR THE WORLD OCEAN

A temperature-salinity diagram outlining the characteristics of all water below the surface layer in the world ocean was prepared by DIETRICH (1950 ; 1957, Abb. 79). His qualitative distribution becomes quantitative in the present results, which differ also in the use of potential temperature and in the inclusion of the surface layer.

For the preparation of this section, Mr. COCHRANE and Mr. POLLAK have supplied complete bivariate distributions for the Pacific and Indian oceans by fine-scale classes (0·5 C $\times$ 0·1 per mille). The water in each class has then been summed over the three oceans to provide a fine-scale working diagram covering the entire range of the world ocean. Fine-scale univariate distributions of potential temperature, salinity, and potential specific-volume anomaly have been prepared from the working diagram. These statistics for the world ocean have been used in preparing Figs. 4 and 5 and Table 2.

The volume stated here for the world ocean is 136,891 $\times$ 10^4 km^3 (the last two digits have no significance). Compared with the liquid sea water represented on the diagrams, the volume of ice in the ocean is very small. By assuming an average ice-covered

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area of 10×10^6 km^2 and an average thickness of 2 m, the volume of sea ice is estimated to be 2×10^4 km^3. The volume of icebergs is presumably smaller by an order of magnitude. The amounts of other waters on the earth, in GOLDSCHMIDT'S (1954) figures, are as follows : The volume of water present as continental ice has been estimated to be $2{,}300 \times 10^4$ km^3. The volume of lakes is about 25×10^4 km^3. The water in rivers and as ground water forms another 25×10^4 km^3. The liquid equivalent of the aqueous vapour in the atmosphere is 1×10^4 km^3.

It is seen on the coarse-scale diagram (Fig. 4) that 75 per cent of the entire ocean falls within the 3 classes from 0 C to 6 C at 34 to 35 per mille. This area is small compared with the total sea-water range from − 2 C to 36 C and from 0 to 44 per mille : most sea water constitutes a vast body that is remarkably homogeneous. From the primary mode at 1 C, 34·5 per mille a subzero limb extends with decreasing salinity as far as 29·5 per mille. The main limb extends along 35 per mille with increasing temperature as far as 23 C. The barely separate (tertiary) mode at 27 C, 35·5 per mille, 500 cl/ton is largely contributed by the Pacific Ocean. The secondary mode, at 13 C, 38·5 per mille, − 85 cl/ton, represents the Mediterranean Sea. The fourth mode, at 9 C, 22·5 per mille, 1,050 cl/ton, represents the Black Sea. The fifth mode, at 21·75 C, 40·6 per mille, − 42 cl/ton, represents the Red Sea deep water, which has remarkably constant characteristics, as may be seen by comparing those given by KRÜMMEL (1907, pp. 358, 474) with those from *Albatross* station 254 used by POLLAK.

The 50-per-cent boundary on the fine-scale diagram (Fig. 5) is rather complex and includes different water types, but they do not form any clearly separate modes. The modal square of 4 classes from 1 C to 2 C and from 34·6 to 34·8 per mille, with potential specific-volume anomaly of 32 cl/ton at the centre, includes the primary modes of the Pacific and Indian oceans. The proportion of the ocean in this modal square is nearly 30 per cent, comprising 44 per cent of the Pacific Ocean, 25 per cent of the Indian Ocean, and only 3 per cent of the Atlantic Ocean. As would be expected for water filling such a large proportion of the ocean, the salinity is close to the mean salinity of the world ocean, 34·72 per mille (Table 2, below). This extensive deep water in the Pacific and Indian oceans may be regarded as the great reservoir of undifferentiated water, the ' Common Water ' from which all special water types differ.

The 50-per-cent boundary extends part way along three limbs protruding from the modal square. The cold limb terminates in Antarctic Bottom Water, the extreme being typically at − 0·9 C, 34·67 per mille, 21 cl/ton. The salt limb represents North Atlantic Deep Water, typically 2·25 C, 34·95 per mille, 18 cl/ton.

The light limb spreads diffusely but is strong as far as the class at 2·75 C, 34·55 per mille, 53 cl/ton. The water in this class occurs in the Atlantic Ocean between 27°S and 49°S at depths from 800 m to 1,600 m, below the salinity minimum, but greater amounts occur in the Indian and North Pacific oceans and, especially, the South Pacific Ocean. This widespread water type, revealed in this quantitative study, seems not to have been mentioned previously.

The secondary mode on the fine-scale diagram occurs at 4·25 C, 34·55 per mille, 67 cl/ton and represents the tropical water type discussed in the preceding section. The tertiary mode, at − 1 C, 34·95 per mille, 0 cl/ton, represents the deep water in the Arctic and Greenland-Norwegian seas.

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There is a fourth mode at 8·25 C, 34·65 per mille, 108 cl/ton. This strange mode is composed of water in the South Pacific, North Pacific, Indian, and South Atlantic oceans, in order of decreasing volume. The Atlantic occurrences are at depths near 500 m at *Meteor* stations 46, 74, and 180.

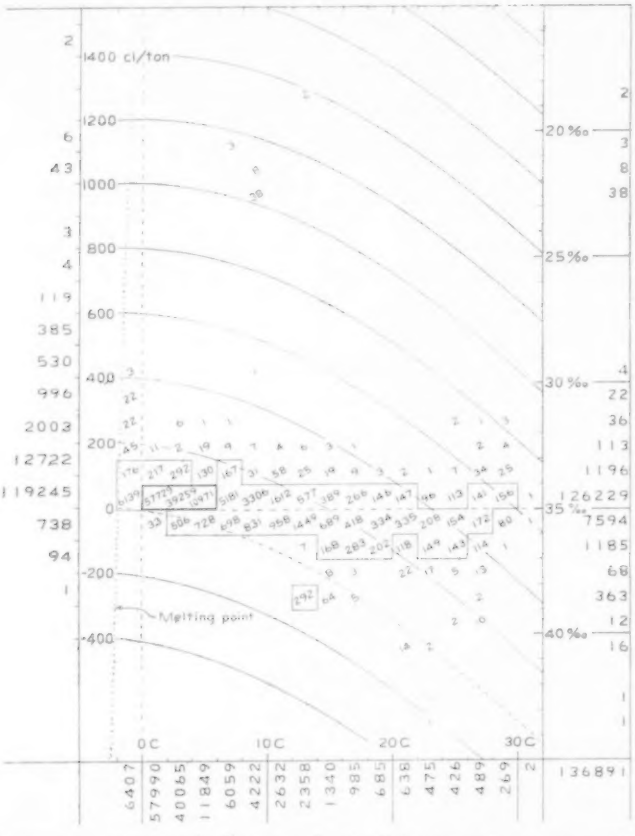

Fig. 4. World ocean on coarse-scale diagram of potential temperature against salinity. Potential specific-volume anomaly is represented by curves. Oblique numbers give 10^4 km^3 of water in each bivariate class 2 C × 1 per mille. Heavy boundary encloses 75 per cent of water (classes with 10971 × 10^4 km^3 or more), fine boundary encloses 99 per cent (141 × 10^4 km^3 or more). Sums at bottom give the distribution by potential temperature, at right by salinity, and at left by potential specific-volume anomaly.

The minor mode at 0·25 C, 34·05 per mille, 71 cl/ton represents water in the Sea of Japan.

The potential-temperature distribution along the bottom of Figs. 4-5 is very skew. The primary mode is at 1·25 C, the modal class containing largely ' Common Water '. There is a subordinate mode at 27 C, largely contributed by the Pacific Ocean.

The salinity distribution is rather symmetrical. The primary mode is at 34·65 per mille and coincides with the ' Common Water '. The secondary mode, at 34·95 per mille, is due to North Atlantic Deep Water. There are subordinate modes at 38·5 per mille (Mediterranean Sea), 22·5 per mille (Black Sea), and 40·5 per mille (Red Sea and Persian Gulf).

The distribution of potential specific-volume anomaly is skew. The primary mode is at 25 cl/ton, the fine-scale modal class containing 31 per cent of the ocean and coinciding with the Atlantic and Indian modes (the Pacific mode is at 35 cl/ton).

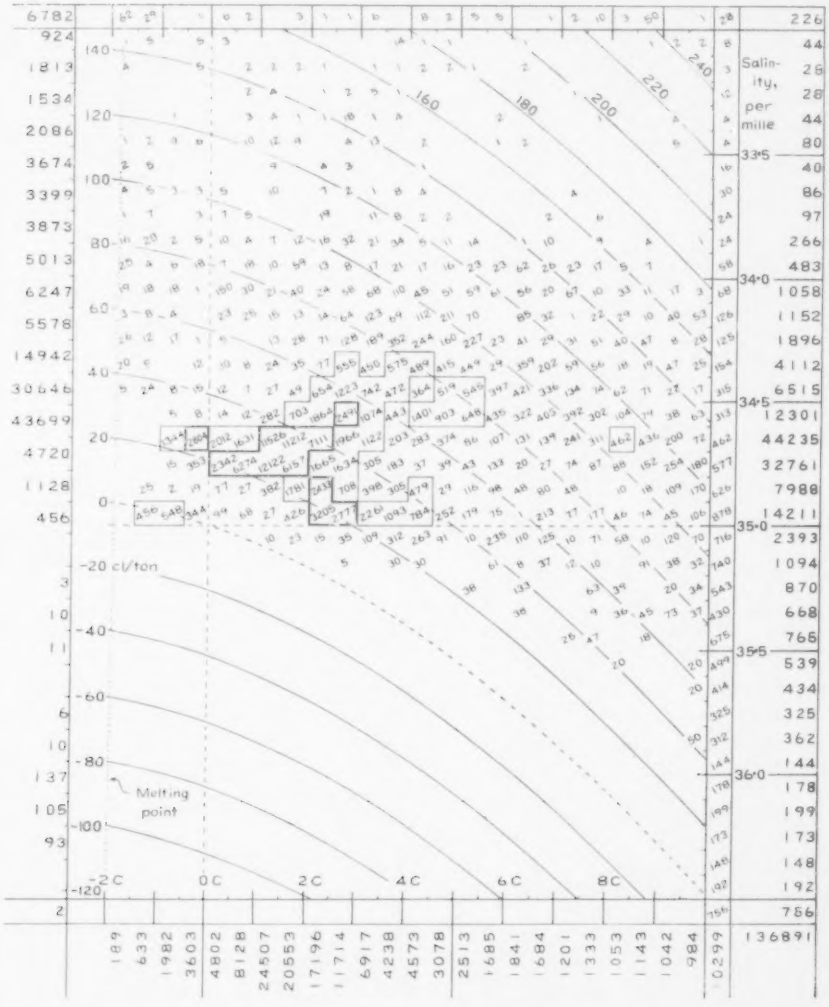

Fig. 5. World ocean on fine-scale diagram of potential temperature against salinity. Potential specific-volume anomaly is represented by curves. Oblique numbers give 10^4 km^3 of water in each bivariate class 0·5 C × 0·1 per mille. Water outside the range of the diagram is represented by oblique numbers in bordering band and amounts to 10497 × 10^4 km^3 or 8 per cent of total. Heavy boundary encloses 50 per cent of total (classes with 2342 × 10^4 km^3 or more), fine boundary encloses 75 per cent (456 × 10^4 km^3 or more). Sums at bottom give the distribution by potential temperature, at right by salinity, and at left by potential specific-volume anomaly.

The secondary mode, at 65 cl/ton, is not pronounced but seems to be a real feature, resulting in part from the tropical water type previously mentioned. The tertiary mode, at 105 cl/ton, may also be real (this class includes the water with characteristics

8·25 C, 34·65 per mille). There are subordinate modes at − 85 cl/ton (Mediterranean Sea), 1,050 cl/ton (Black Sea), and − 42 cl/ton (Red Sea).

Table 2. Means and percentiles

Ocean	*Mean*	5%	25% *Lower quartile*	50% *Median*	75% *Upper quartile*	95%
			Potential temperature, C			
Pacific	3·36	0·8	1·3	1·9	3·4	11·1
Indian	3·72	− 0·2	1·0	1·9	4·4	12·7
Atlantic	3·73	− 0·6	1·7	2·6	3·9	13·7
World	3·52	0·0	1·3	2·1	3·8	12·6
			Salinity, per mille			
Pacific	34·62	34·27	34·57	34·65	34·70	34·79
Indian	34·76	34·44	34·66	34·73	34·79	35·19
Atlantic	34·90	34·41	34·71	34·90	34·97	35·73
World	34·72	34·33	34·61	34·69	34·79	35·10
			Potential specific-volume anomaly, cl/ton			
Pacific	62	22	31	39	66	162
Indian	56	21	25	31	63	145
Atlantic	45	8	22	28	46	137
World	56	20	26	36	62	149

Table 2 presents mean potential temperatures computed from volumes by classes of 0·5 C, mean salinities by classes of 0·1 per mille, and mean potential specific-volume anomalies by classes of 10 cl/ton (the last determined by the centre of each bivariate class 0·5 C × 0·1 per mille, as explained in the first section). It is remarkable that the mean potential temperatures hardly deviate significantly, when increased by about 0·2 C to regain actual temperatures, from KRÜMMEL's (1907, p. 495) mean actual temperatures, namely, Pacific 3·7 C, Indian 3·8 C, Atlantic 4·0 C, world ocean 3·8 C. KRÜMMEL (1907, p. 344) said that the measurements available did not suffice for a calculation of mean salinity, but he was inclined to assume " etwa 34·7 bis höchstens 34·8 Promille " as mean salinity of the open ocean. This estimate also is corroborated.

It may be noted that for each ocean the mean potential specific-volume anomaly is about 10 cl/ton greater than the potential specific-volume anomaly corresponding to the mean potential temperature and mean salinity. The latter value would be attained if the ocean were homogenized adiabatically. The ocean would contract by 1 part in 10^4, or by 14×10^4 km^3. The area of the sea surface being 361×10^6 km^2, sea level would fall by 0.4 m.

Table 2 also lists medians, quartiles, and 5-percentiles. From these statistics can be seen, as examples, that the potential temperature of half the ocean is below 2·1 C and that the salinity of half the ocean is between 34·61 and 34·79 per mille.

In general terms, the bivariate distribution of the water in the world ocean by classes 0·5 C × 0·1 per mille has revealed the following features : There is a dominant mode at potential temperature 1·5 C, salinity 34·7 per mille, potential specific-volume anomaly 32 cl/ton (' Common Water '). This is the only mode within the 50-per-cent boundary, but limbs represent three additional water types. Outside the 50-per-cent boundary there are several rather indistinct modes representing water types in the

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open ocean. There are a number of sharper modes representing deep water in basins isolated from the open ocean.

Acknowledgements—The author is grateful to Mrs. N. GOLDIE, Stirling, Scotland, and to Dr. ARNOLD COURT, U.S. Department of Agriculture Forest Service, Berkeley, California, for helpful correspondence regarding boundaries of stated percentage and bivariate distributions.

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Contribution No. 36 *from Chesapeake Bay Institute. This study was supported in part by the Office of Naval Research and by a research grant from the National Science Foundation.*

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Biogeographical regions of the plankton of the North-Western Pacific Ocean and their influence on the deep sea

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(*Received* 21 *October*, 1957)

Abstract—Biogeographical regions in the pelagial of the ocean can and should be characterized not only by their typical species but also by their production of plankton. The biomass of plankton (weight in mg per 1 m^3) in the boreal region of the North Pacific Ocean is about ten times greater than in its tropical region. Since plankton is the basis of all food-relationships through the whole thickness of the ocean water mass, this will tell also on the abundance of benthos and the character of bottom sediments. The boreal region is richer in benthic life and its sediments contain a greater amount of silica.

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INTRODUCTION

WITH the rapid development of fisheries – which depend either directly or indirectly on plankton-feeders – a knowledge of plankton is especially important. It can lead to an evaluation of marine resources and even to the possibility of forecasting their utilization by man. Consequently, it is important to ascertain the distribution (horizontal, vertical and seasonal) of various plankton organisms and to determine other features of the biogeographical areas affecting the distribution of many fish*, whales* and squid. In the Pacific Ocean, the distribution of the surface calanoids has been delimited by BRODSKY (1955-1956) and corroborated by others. There is nevertheless a need for more detailed studies of the plankton, its composition and amount (biomass), the number of generations, primary production, etc., typifying different areas, as related to the water masses. An attempt at such an evaluation has been made possible by the data collected in the North-Western Pacific by expeditions of the Institute of Oceanology of the U.S.S.R. Academy of Sciences on the *Vitiaz*.

The present paper is based on observations made by the author and on the following published papers: ANRAKU (1953; 1954), BEKLEMISHEV and SEMINA (1956), BOGOROV and BEKLEMISHEV (1955), BRODSKY (1950-1956), FUKUOKA (1955), HIRANO (1957; 1957a), KAWAI (1955; 1956a; 1957b), LUBNY-GERZYK (1956), MOTODA and ANRAKU (1954; 1955), NAKAI (1952), PONOMAREVA and BEKLEMISHEV (1956), SEMINA (1956), SMIRNOVA (1956), TANAKA (1953), VINOGRADOV (1954-55) and WILSON† (1942-1950).

PHYSICAL AND BIOLOGICAL CHARACTERISTICS OF THE SURFACE WATERS

It is more convenient to accept three biogeographical regions in the part of the Pacific Ocean: arctic, boreal and tropical, without any further subdivision into subtropical, subarctic, etc. The southern limit of the arctic region extends to the southern Chukchi Sea, where arctic and boreal forms intermingle. Over 50 per cent of the plankton fauna consists of Bering Sea or arctic species (BRODSKY, 1955a) and the remainder are representatives of Pacific boreal communities, including *Eucalanus*

*See p. 159.
†Some of Wilson's identifications are not reliable, so that his papers are only partly used.

bungii, *Calanus cristatus*, *Calanus plumchrus*, etc. The boreal waters extend northward from the line 40°-42°N. Here the Oyashio (or Kurile-Kamchatka) Current flows from the Bering and Okhotsk Seas. In winter and spring the well-cooled waters of the Okhotsk Sea enter the Pacific through the passage between the southern and central Kurile Islands. Consequently, the southern waters of the Kurile-Kamchatka region are colder in spring than its northern waters.

The surface waters in the Pacific between the line 40-42°N and the Kurile Islands usually have a temperature in winter of less than 3°C, increasing in summer to 14°-15°C, where the cold Oyashio waters meet the warm waters of the north-eastern branch of the Kuroshio, forming a subarctic convergence, termed also as the primary polar front or the Oyashio front (MASUZAWA, 1955). To the south of the front, the waters of the Oyashio and Kuroshio intermingle and are characterized by a surface temperature of 18°-20°C in summer. This " zone of mixing," the " zone of transition " of BOGOROV and VINOGRADOV (1955a)*, varies in width with the season and the prevailing winds. Probably a zone of mixing of boreal and tropical faunas also occurs in the Southern Sea of Japan and the Yellow Sea. The tropical waters of the Kuroshio with surface temperatures of 26°-28°C in summer and 18°-20°C in winter are dominant south of 35°N.

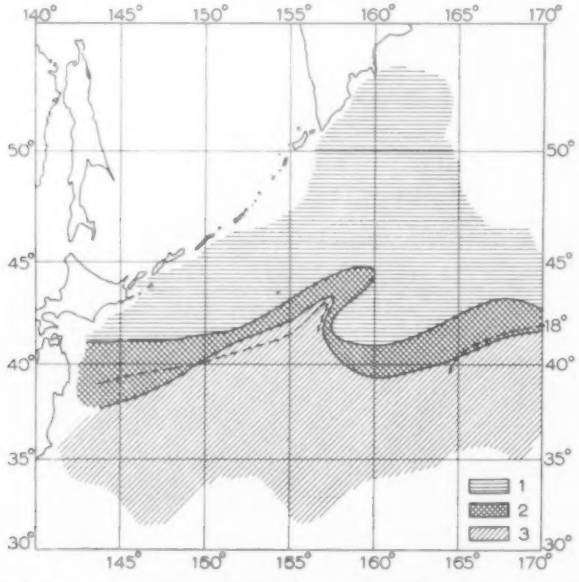

Fig. 1. Distribution of zooplankton communities in the surface waters in the North-Western Pacific. August-October 1954. (1) Boreal complex; (2) Zone of mixing; (3) Tropical complex. Broken line is an isotherm of 18° on the surface water (from B. G. BOGOROV and M. E. VINOGRADOV, 1955).

The composition of the plankton in these waters varies greatly (Fig. 1; Tables 1-3)†, but contrary to BRODSKY's (1955) opinion that a distinct subtropical plankton fauna occurs between the boreal and tropical faunas, no such group was found. Just as the

*The term " zone of mixing " is preferable.

†South of 40°N, and especially south of 35°N, coccoliths, *Cestus amphitrites*, *Velella*, *Physalia*, heteropods, pteropods, salps, *Halobates*, etc., should also be included as typical.

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Table 1. Copepods found in the "zone of mixing" (surface layers down to 200 m): their distribution in boreal and tropical waters based on various published data* BRODSKY, 1950; ANRAKU, 1954; NAKAI, 1952; TANAKA, 1955; WILSON, 1942; 1950† *and the author's own collections*

Species	*Temperature* Om.		
	from 3° *to* 15°	*from* 15° *to* 18°	*from* 18° *to* 27°
	Boreal waters	*Zone of mixing*	*Tropical waters*
Calanus cristatus	+	+	–
Calnus pacificus	+	+	–
Calanus plumchrus (*tonsus*)	+	+	–
Candacia columbiae	+	+	–
Eucalanus bungii	+	+	–
Labidocera japonica	+	+	–
Metridia ochotensis (*longa*)	+	+	–
Metridia pacifica (*lucens*)	+	+	–
Microcalanus pygmaeus	+	+	–
Oncaea borealis	+	+	–
Pareuchaeta japonica	+	+	–
Pseudocalanus elongatus (*minutus*)	+	+	–
Scolecithricella minor	+	+	–
Calanus tenuicornis	+	+	+
Candacia bipinnata	+	+	+
Clausocalanus arcuicornis	+	+	+
Eucalanus attenuatus	+	+	+
Euchirella brevis	+	+	+
Gaidius tenuispinus	+	+	+
Microsetella rosea	+	+	+
Oithona plumifera	+	+	+
Oithona similis	+	+	+
Oncaea conifera	+	+	+
Paracalanus parvus	+	+	+
Acartia danae	–	+	+
Acartia negligens	–	+	+
Acrocalanus gibber	–	+	+
Acrocalanus gracilis	–	+	+
Aetideus armatus	–	+	+
Calocalanus pavo	–	+	+
Calocalanus plumulosus	–	+	+
Candacia simplex	–	+	+
Candacia varicans	–	+	+
Clausocalanus furcatus	–	+	+
Clausocalanus pergens	–	+	+
Clytemnestra rostrata	–	+	+
Copilia mirabilis	–	+	+
Copilia quadrata	–	+	+
Corycaeus anglicus	–	+	+
Corycaeus crassiusculus	–	+	+
Corycaeus pumilus	–	+	+
Corycaeus speciosus	–	+	+
Corycaeus typicus	–	+	+
Eucalanus crassus	–	+	+
Eucalanus mucronatus	–	+	+
Eucalanus subcrassus	–	+	+
Eucalanus subtenius	–	+	+
Euchaeta acuta	–	+	+
Euchaeta marina	–	+	+
Farranula gibbula	–	+	+
Farranula rostrata	–	+	+
Gaetanus minor	–	+	+
Haloptilus angusticeps	–	+	+

*Prepared with the assistance of A. K. HEINRICH.

†See Footnote † on page 149.

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Table 1—continued.

Species	Temperature Om.		
	from 3° to 15°	*from 15° to 18°*	*from 18° to 27°*
	Boreal waters	*Zone of mixing*	*Tropical waters*
Heterorhabdus papilliger	—	+	+
Labidocera acuta	—	+	+
Labidocera detruncata	—	+	+
Lucicutia clausi	—	+	+
Lucicutia flavicornis	—	+	+
Macrosetella gracilis	—	+	+
Mecynocera clausi	—	+	+
Megacalanus princeps	—	+	+
Nannocalanus minor	—	+	+
Neocalanus gracilis	—	+	+
Oithona attenuata	—	+	+
Oithona nana	—	+	+
Oithona setigera	—	+	+
Oithona spinirostris	—	+	+
Oncaea media	—	+	+
Oncaea mediterranea	—	+	+
Oncaea minuta	—	+	+
Oncaea venusta	—	+	+
Paracalanus aculeatus	—	+	+
Paracalanus pygmaeus	—	+	+
Phaenna spinifera	—	+	+
Pleuromamma gracilis	—	+	+
Rhincalanus nasutus	—	+	+
Sapphirina auronitens	—	+	+
Sapphirina nigromaculata	—	+	+
Sapphirina stellata	—	+	+
Temora discaudata	—	+	+
Temora stylifera	—	+	+
Temora turbinata	—	+	+
Undinula darwini	—	+	+
Undinula vulgaris	—	+	+
Xanthocalanus pauper	—	+	+

water in the area of convergence is the product of a mixing of the boreal and tropical waters, so too the plankton of the surface layers is the product of an intermingling of species living in both water masses (Table 1). By inference, the " zone of mixing " is inhabited by the most eurythermal species from the boreal and tropical waters.

The phytoplankton contains 58 per cent of diatoms, 38 per cent of peridinians and 4 per cent of cyanophycean and silicoflagellates (SMIRNOVA, 1956). There is a marked preponderance of diatoms in the boreal region – three to four times the number of peridinians – both in the number of species and especially in biomass. Inversely, in tropical waters there are twice as many species as in boreal waters (Table 2). The zone of mixing contains almost equal percentages of phytoplankton species from warm (tropical), temperate-warm (southern boreal) and temperate-cold (northern boreal) waters (cf., Tables 2 and 3).

Comparison of Figs. 1 and 2 shows that the boundaries of the biogeographic regions and zone of mixing are the same. As already mentioned, the zone of mixing shifts considerably according to the season. In winter, the boreal fauna extends southwards, and in spring the zone of mixing lies south of 40°N. In the summer the distribution of tropical fauna extends northwards across the zone of mixing and in the autumn the zone of mixing stretches up to 42°N. The farther northwards from the main flow of the Kuroshio, the thinner becomes the layer of mixed water. Near

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42°N the tropical representatives live in the uppermost water layers down to 50 m, less frequently to 100 m. Below this depth occur mainly representatives of the boreal fauna. Some of them are found also farther south but at ever increasing depths;

Table 2. Phytoplankton species in the several types of water in the North-Western Pacific

Type of Water	*No. of Species recorded*	*Representative species*
Cold water (i.e., chiefly arctic region)	10	Ceratium arcticum Rhizosolenia alata f. curvirostris Rhizosolenia hebetata f. hiemalis (all have wider distribution)
Temperate cold water (i.e. chiefly northern part of boreal region)	27	Ceratium fusus Ceratium longipes Chaetoceros altanticus Chaetoceros concavicornis Thalassiosira nordenskiöldii
Temperate warm water (i.e., chiefly southern part of boreal region)	19	Ceratium tripos Ceratium macrosceros Chaetoceros affinis Chaetoceros convolutus Thalassiosira subtilis
Warm water (i.e., tropical region)	55	Ceratium extensum Ceratium massiliense Ceratocorys armata Ceratocorys horrida Chaetoceros coarctatus Chaetoceros lorenzianus Chaetoceros peruvianus Chaetoceros messanensis Climacodium biconcavum Ethmodiscus rex Pyrocystis pseudonotilina Pyrocystis fusiformis Pyrocystis hamulus Rhizosolenia bergonii Trichodesmium thiebauti

Table 3. Percentages of the total number of species of phytoplankton population in the North-Western Pacific Ocean arranged according to their ecological affinities (SMIRNOVA, 1956)

	Warm-water species 11°-25°C with preference for temperatures above 18°C	*Temperate warm-water species 5°-10°C*	*Temperate cold water species 3°-14°C with preference of 5°-10°C*	*Cold-water species 2°-5°C*
Boreal waters	1%	13%	79%	7%
Zone of mixing	35%	30%	35%	—
North-eastern branch of the Kuroshio	93·5%	6%	0·5%	—

in the northern part of the Kuroshio they live at depths of 1000 m and more. At these depths the character of the plankton fauna tends to be much the same in all areas.

The biogeographical regions differ from one another not only in the species occurring there, but also in the abundance of certain species, In the arctic region only two species are abundant: *Calanus finmarchicus* and *Pseudocalanus elongatus* (*minutus*). In the surface zone (0-200 m) of the boreal region, there are several abundant species : *Calanus plumchrus, Calanus cristatus, Eucalanus bungii, Metridia pacifica* and *Oithona similis*. In the southern boreal region, this plankton is superceded or complemented by a number of warm water species: *Calanus pacificus, Eucalanus hyalinum* and others. Farther south off the Kurile Islands *Penilia avirostris* occurs.

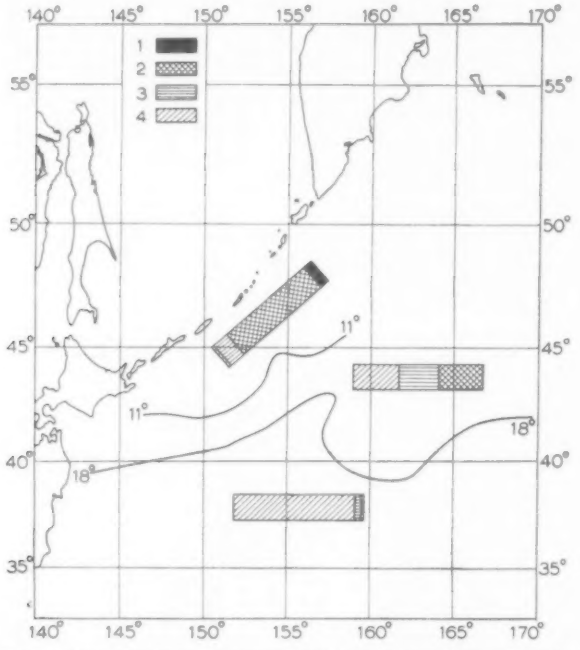

Fig. 2. Characteristic of phytoplankton (in percentage from all numbers of species) in Boreal waters, Zone of mixing and northern waters of Kuroshio. (1) Cold water species; (2) Temperate-cold water species; (3) Temperate-warm species; (4) Warm-water species. August-October 1954.

The passage to the tropical region can be recognized by the appearance of flying fish, sharks, moonfish, etc. No abundant species (i.e., with respect to biomass) are found in the plankton in the tropical Pacific Ocean, but there is usually a great variety of species. In the surface waters the calanoids alone are represented by more than 100 species.

The biomass (weight of plankton per m^3) is distributed in the north-western part of the Pacific (Fig. 3) as follows: near the Kurile Islands the quantity of plankton usually averages 200 mg per m^3, with a sharp increase further south and also further offshore, in a band 30-50 miles wide. Here the biomass usually exceeds 500 mg, and in some places even 2000 and 3000 mg per m^3 (BOGOROV and VINOGRADOV, 1955). Comparison of plankton in spring and late summer indicates that this area of high zooplankton biomass is fairly stable. Patches with large quantities of plankton are also encountered elsewhere in the boreal region. Occasionally larger amounts may also occur near shore. The nearer to the tropics the less plankton there is. The warm

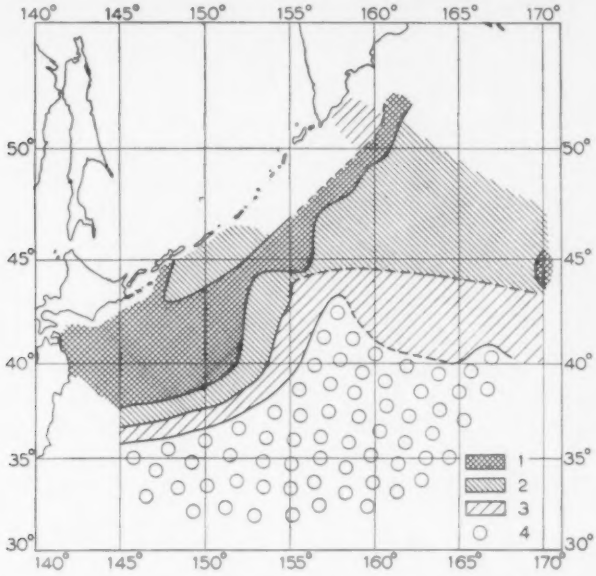

Fig. 3. Distribution of Zooplankton biomass in 0-100 m in the North-Western Pacific August-October 1954. (1) > 500 mg/m³; (2) 250-500 mg/m³; (3) 100-200 mg/m³; (4) < 100 mg/m³ (from B. G. Bogorov, M. E. Vinogradov, 1955).

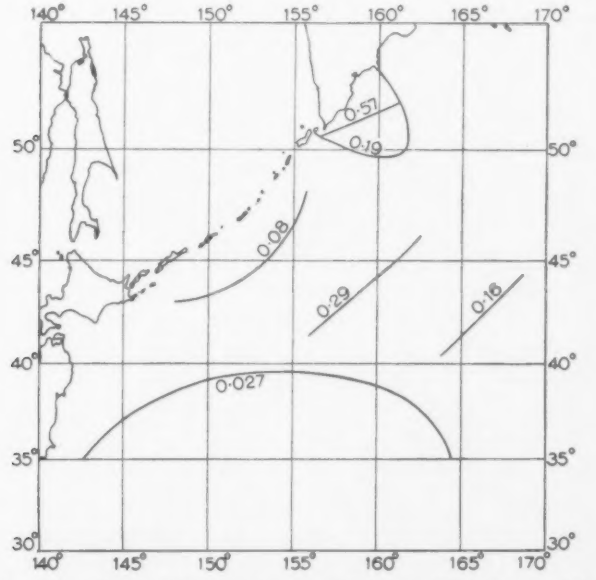

Fig. 4. Average diurnal production of carbon in mg per litre in a different part of the North-Western Pacific. August-October 1954 (determined by Oxygen method). After B. G. Bogorov and C. W. Beklemishev, 1955).

waters of the Kuroshio are characterized by a low plankton biomass, usually less than 100 mg/m^3, and often below 50, or even 20 mg. In the regions between 40° and 50°N the quantity of plankton is many times greater than south of 30°N (NAKAI, 1952).

The low primary production of tropical waters results in a low biomass of phytoplankton. Carbon production as determined by the oxygen method on the *Vitiaz* in 1954 (BOGOROV and BEKLEMISHEV, 1955) was ten times lower in the tropical region than in the boreal (Fig. 4). In areas where the phytoplankton at that time was " in bloom," i.e., at its maximum, along the shores of Kamchatka, primary production was 20 times greater than in the tropical region.

The low biomass of plankton in tropical waters seems inconsistent with the great numbers of large sharks and fishes dwelling there. Presumably, it is compensated for by a high rate of breeding, i.e., by a great number of generations, whereas in boreal regions the number of generations is limited. In the Bering Sea (HEINRICH, 1956) and the Kurile-Kamchatka region, for example, there are but two well expressed maxima for reproduction of *Calanus plumchrus*: a vernal one and one in the summer-autumn months. However, some reproduction also takes place throughout the year, as few young are always present.

VERTICAL DISTRIBUTION OF PLANKTON

In a study of the vertical distribution of plankton the ocean is divided into a series of zones from top to bottom (BOGOROV, 1948). Down to 200 m is the surface (BIRSTEIN, VINOGRADOV and TCHINDONOVA, 1954) or producing zone, where the phytoplankton grows. In the Bering Sea, it is well mixed owing to seasonal vertical circulation and receives a relatively great amount of light. This zone can be subdivided into two sub-zones: an upper one extending from the surface to 100 m, well illuminated and producing the main mass of phytoplankton, and a lower one from 100 to 200 m, partially illuminated and poor in phytoplankton.

Characteristic of the surface zone of the boreal region in the North-Western Pacific are the following zooplankton species: *Calanus plumchrus*, *Eucalanus bungii*, *Calanus cristatus*, *Sagitta elegans*, *Euphausia pacifica*, *Thysanoessa longipes*, *Parathemisto japonica*, *Cyphocaris challengeri*, *Dimophyes arctica*. In this zone interzonal bathypelagic crustaceans, which ascend into the upper layers at night are also encountered. The biomass of plankton in this zone reaches 1000 mg/m^3 or more.

The transition zone extending from 200 to 500 m, is a consuming zone, devoid of phytoplankton. The zooplankton contains many interzonal species, migrating between the surface and the deep-sea zone. Characteristic deep-sea dwellers are the young of *Hymenodora frontalis* and *Gnathophausia gigas*, *Primno macropa*, *Scina borealis*, *Sc. incerta*, *Scaphocalanus magnus*, *Pseudochirella spinifera*, *Haloptilus pseudoxycephalus* and others. This zone is generally richer in species than the surface zone, but far poorer in biomass, the latter decreasing to 350 mg/m^3.

The whole water mass below 500 m was formerly considered as a single deep-water zone (BOGOROV, 1948 and others), but BRODSKY (1955b) divided it into two parts: 1000-3000 m and 3000-bottom. In analysing the abyssal plankton in the Kurile Trench, the depths of more than 500 m have been divided into two zones: a deep-sea zone with depths ranging from 500 to 6000 m and a zone of depression with depths exceeding 6000 m (BIRSTEIN, VINOGRADOV and TCHINDONOVA, 1954). In the former there is a specificity and variety of plankton fauna and a low biomass (2·64-78 mg/m^3).

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Many of these animals are red or brownish red in colour. In the latter there is an extreme paucity of zooplankton, both quantitative and qualitative. Its biomass is less than 1 mg/m^3 (0·48 mg/m^3). It is inhabited chiefly by certain species of copepods, amphipods and ostracods, many of which have a whitish colouring.

In May-June 1953, in the Kurile-Kamchatka Trench, the total biomass of zooplankton contained under 1 m^2, in a water column almost 10 km deep, was distributed as follows: 31 per cent in the upper 200 m (the uppermost layer (0-50m) containing over 10 per cent), 31·8 per cent in the transition zone (200-500 m), 35 per cent in the deep-sea zone, a layer of 5500 m, and 2 per cent in the zone of depression, a layer of 4000 m (VINOGRADOV, 1954).

DISCUSSION

The composition of faunas and floras is not the only difference in the biogeographical regions of the North-Western Pacific. The boreal differs from the tropical region in many other features, such as the structure of the water masses, ways to enrich the surface layers with biogenic matter, a greater primary production and biomass of plankton throughout the water column, a different number of generations, etc. All these effect the conditions of life throughout the water mass. The physical and chemical characteristics of bottom waters, on the other hand, are quite similar everywhere. The only obvious difference is the abundance and composition of plankton produced at the surface in boreal and tropical regions. Hence, in ways not yet exactly known, food interrelationships probably influence the distribution of the benthos, although isolation in depressions also leads to endemism.

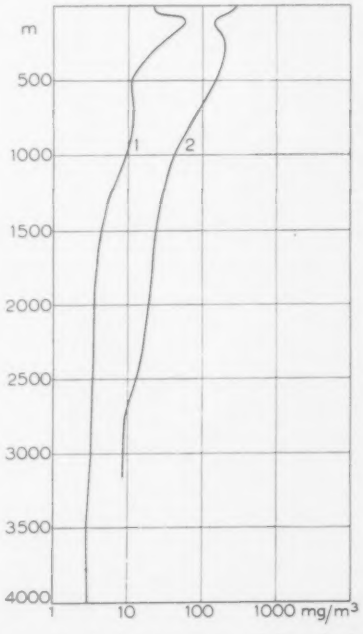

Fig. 5. Vertical distribution of Zooplankton biomass in different layers on the deep-water stations in the North-Western Pacific. (1) Tropical waters; (2) Boreal water (from B. G. BOGOROV and M. E. VINOGRADOV, 1955a).

Differences in the abundance of life in the boreal and tropical regions are the main cause of differences observed in the amount of organic matter in muds deposited in these regions (see Figs. 3 and 6). The muds, benthos and deep-sea near-bottom dwellers bear the imprint of all processes going on above them, especially those taking place in the surface zone. This influence of the surface zone can be used in palaeogeographic-estimates of bottom deposits.

Comparison of the quantities of zooplankton at various depths throughout the water column at deep-water stations (BOGOROV and VINOGRADOV, 1955a) in boreal and tropical regions (Fig. 5) reveals a lower biomass at all depths in the tropical

region (Fig. 5). Thus, it may be presumed that a scanty plankton in the producing surface zone affects the whole column even to great depths.

Oceanologically, this great poverty of deep-sea plankton in the tropical region, as compared with the boreal, has many causes. One of the most important, the enrichment of nutrient salts brought up from greater depths, is effected by the winter cooling and subsequent mixing, a process which is weak in the tropics. In the boreal region, also, the summer thermocline, within the surface zone, inhibits the sinking of phytoplankton below the illuminated photosynthetic layer (SEMINA, 1955). The boreal region, furthermore, covers a smaller area and therefore receives relatively more biogenic matter from river effluent to enrich it.

Obviously, the vertical distribution of zooplankton and the closely interlocked food-relationships of animals living in different layers cannot be understood without a knowledge of their migrations. There is an absence of diurnal migrations in many surface species (VINOGRADOV, 1954a). Inhabitants of the surface and intermediate

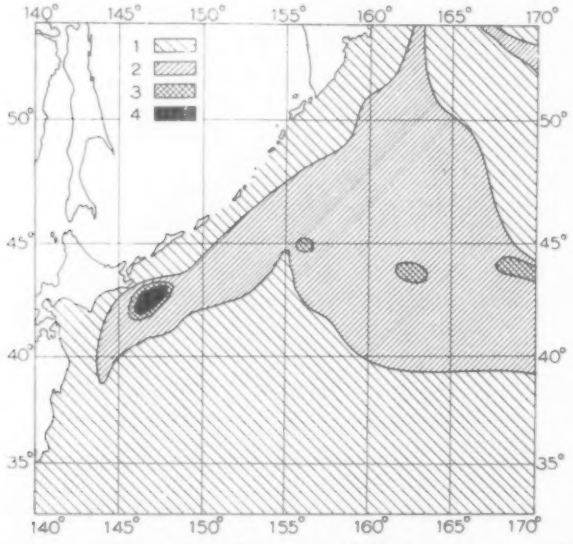

Fig. 6. Distribution in sediments of amorphous silica (SiO_2) produced by diatoms in the North-Western Pacific in percentage of dry weight of sediment. (1) + 10%; (2) 10-20%; (3) 20-30%; (4) > 30%. (Composed by P. L. BEZRUKOV).

zones such as *Calanus plumchrus* and *Eucalanus bungii*, have extensive seasonal and ontogenetic migrations, but do not descend below 50 m, seldom to 100 m during diurnal migrations. On the other hand, *Metridia pacifica*, *Metridia ochotensis Parathemisto japonica* and other species, with no extensive seasonal migrations, carry out diurnal migrations up to 400-500 m. As yet, it has not been possible to investigate in detail the migrations of inhabitants of the deep-sea zone, though we know that it exists.

Through the diurnal, seasonal and ontogenetic migrations of plankton organisms,

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particularly of the abundant copepods*, which form the greatest proportion of the biomass, enormous amounts of organic matter are transported downward from the producing surface layers to the deep water. The bottom plankton feeds on sinking dead bodies and fecal pellets, as well as on living organisms. The stomach contents of deep-sea decapods and amphipods indicate that they are carnivorous rather than filter feeders. Many Euphausiacea, Mysidacea and Isopoda, during their migrations in the surface layers feed not only on animals, but also on phytoplankton. Deep-sea copepods are carnivorous feeding on Radiolaria and other small animals. All crustaceans, in their turn serve as food to small deep-sea fish (BIRSTEIN and VINOGRADOV, 1955). Thus, herbivorous feeding which prevails in the surface zone, is superseded in deep water by feeding on living animals or on detrius.

Peculiarities in the biogeographical distribution of plankton can be traced too in the peculiarities of sedimentation. Zones of bottom deposits with high silica content correspond to regions rich in plankton biomass.

Great quantitites of plankton characteristic of boreal waters (Fig. 3) are indicative of areas where fishes such as the saury (*Coloblabis saira*) concentrate (RASS, 1955; PARIN, 1956; Fig. 7). Also, in the North-West Pacific, the Japanese salmon fishery (NAKAI, 1952) and whaling (UDA, 1953; 1954) occur in regions of plankton abundance.

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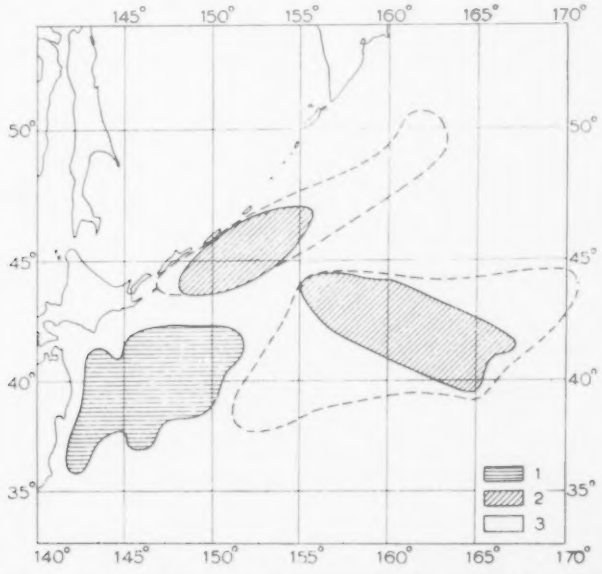

Fig. 7. Distribution of pelagic fish in the North-Western Pacific. (1) Region of Japanese fishing of *Cololabis saira*; (2) Regions of the Concentration of *Cololabis saira* was determined in August-October 1959; (3) Hypothetical distribution of *Cololabis saira* in August-October 1954. (After T. S. RASS and N. B. PARIN).

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*Most surface copepods feed chiefly on diatoms, even the large ones with hard siliceous shells or long bristles (BEKLEMISHEV, 1954). The herbivorous copepods crush these with mandibular crowns of silica as hard as the diatom shells (BEKLEMISHEV, 1954a). The teeth of the masticatory surfaces of the mandibles of the predatory species (*Pareuchaeta*, *Bathycalanus*, etc.) are set far apart, are sabre-shaped and adapted mainly for grasping (BEKLEMISHEV, 1954a). Adult *Calanus cristatus*, *C. plumchrus* and male *Eucalanus bungii*, which do not feed in the adult stage, have no mandibular crown.

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Sounding Profiles between Fiji, Christmas and Tahiti Islands

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(*Received* 25 *April* 1958)

Abstract—Three sounding profiles in the South West Pacific are described and an attempt made to classify the different types of terrain recorded by echo sounder.

INTRODUCTION

IN 1956 H.M.N.Z.S. *Lachlan*, the Royal New Zealand Naval Survey Ship, had occasion to make an extended voyage in the South West Pacific during which constant echo-sounding was carried out over 4500 sea miles embracing three long profiles as follows :

Profile 1. Fiji to Christmas Island.

Profile 2. Christmas Island to Tahiti.

Profile 3. Tahiti to Fiji.

As this area appears to have been little investigated, it has been considered worthwhile to reproduce these profiles as they reveal something of the nature of the sea bed.

An attempt has also been made to classify the different districts passed over in the categories used by KOCZY (1954), these being " plains," " hill districts " and " volcanic tectonic " (here called " volcanic ") regions. However, in attempting to do this along these profiles, it has been found necessary to include also a " mountainous district " when a considerable mass of rugged features rise more than 5000 ft above the general level of the sea bed and when the slopes of such a mass do not indicate volcanic structure.

Where excessively smooth topography is found along these profiles it appears to be on gentle slopes in the vicinity of, and stretching away from, features which are apparently the result of volcanic action. These smooth areas have been included in " volcanic " regions for classification in this paper but are shown in a thick line on the profile diagrams. Such slopes fit the classification " Archipelagic aprons " given by MENARD (1956) to the distinctive long smooth curves which are interrupted sometimes by steep-sided hills rising abruptly from them, but without deep areas of sea-bed below the general level of the smooth surface, and where sediment appears sometimes to be ponded behind ridges.

METHOD

The survey ship was fitted with an asdic set type 128 C.V.S. with type A/S.49 recorder, the dome being fitted with a baffle to deflect pulses towards the sea bed. These pulses reflected from the sea bed were graphically recorded on iodized paper. Sometimes the mark on the paper indicating depth was weak and did not endure, so that the depth had to be pencilled in carefully every $\frac{1}{4}$ hr or so.

The three profiles are drawn on an exaggerated vertical scale in Figs. 1-3. Fig. 4 shows the track followed on the scale of 1/10,000,000 which is that used for the

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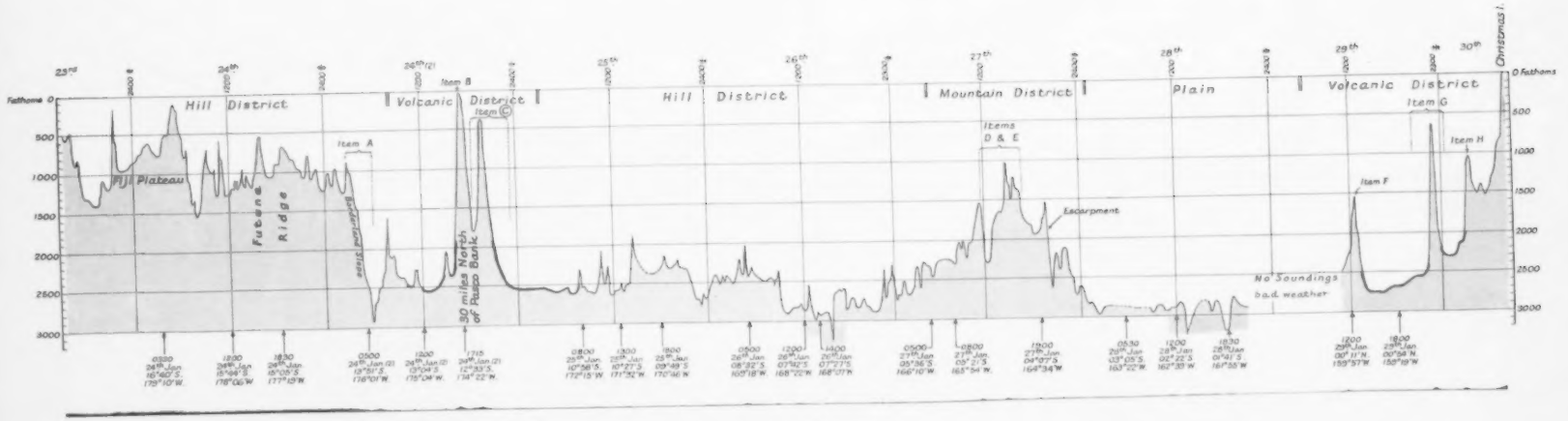
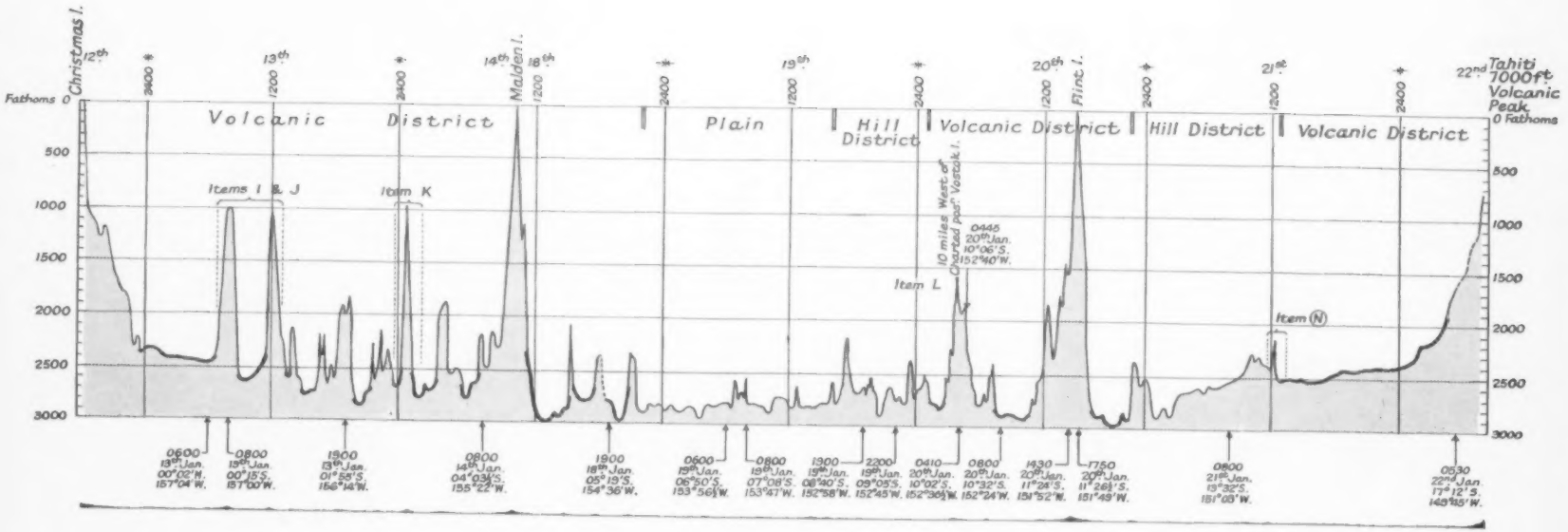


Vertical exaggeration 100-1 (approx.)

Fig. 1. Profile Fiji to Christmas Island.



Vertical exaggeration 100-1 (approx.)

Fig. 2. Profile Christmas Island to Tahiti.

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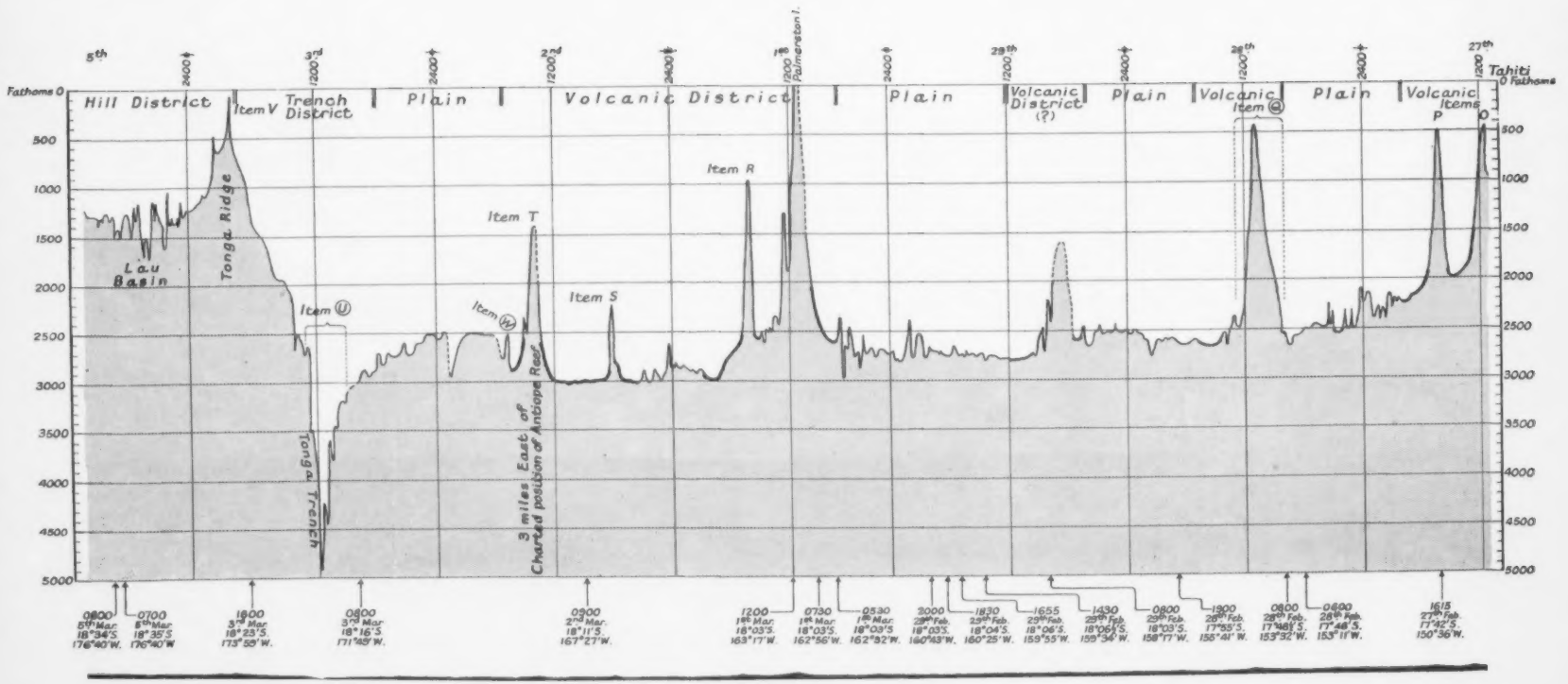
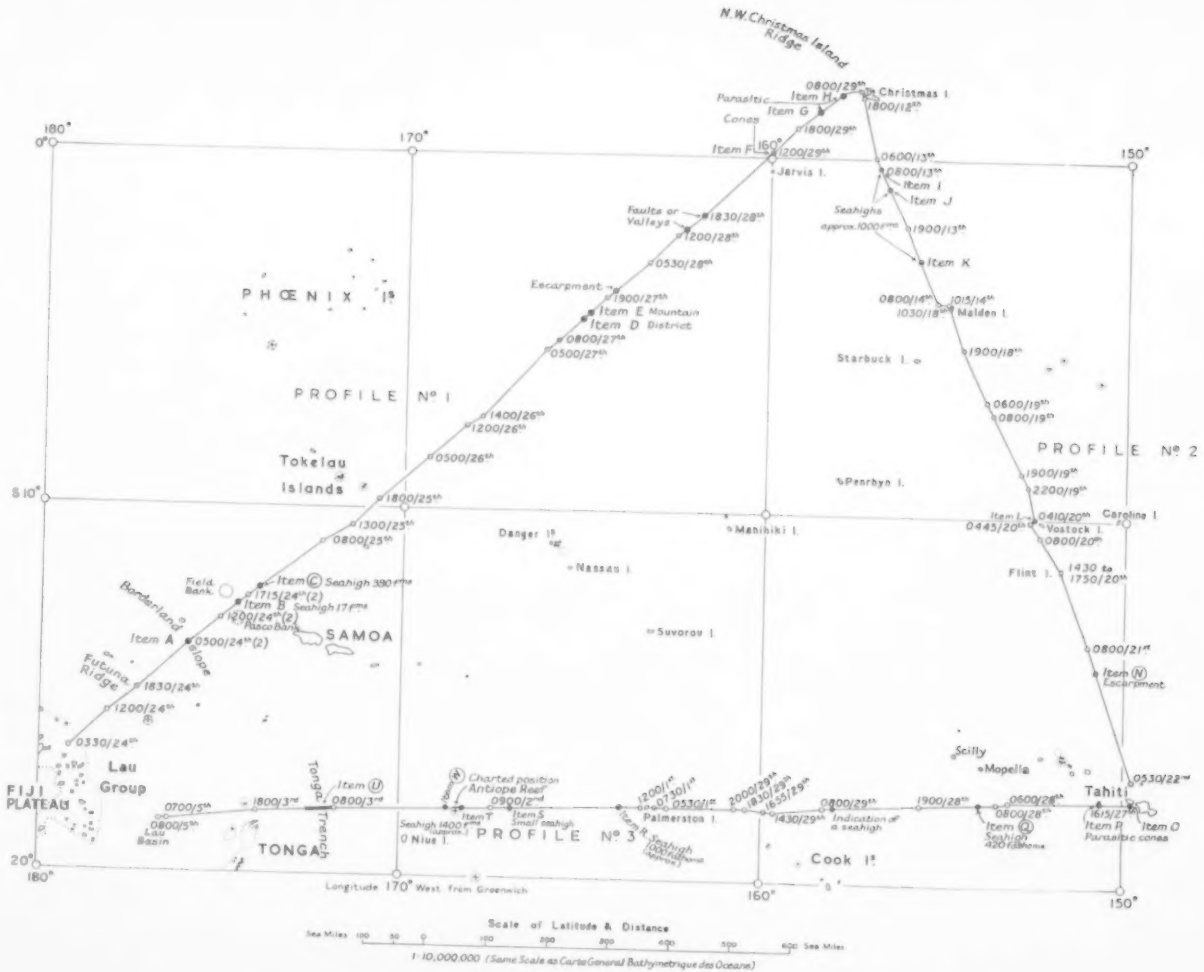


Vertical exaggeration 120-1 (approx.)

Fig. 3. Profile Tahiti to Fiji.



Sounding Track of H.M.N.Z.S. *LACHLAN* January-March 1956.

Fig. 4.

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general bathymetric charts of the world published by the International Hydrographic Bureau at Monaco. The ship's position was fixed by taking normal sun and star sights, the weather conditions being generally favourable, and it is considered that an accuracy of $\pm$ 2·0 miles may reasonably be claimed for these sights. The times of fixing are shown on Fig. 4, while the geographical co-ordinates of the fixes are given against the corresponding times on Figs. 1-3. The positions of certain features along the profiles have been marked on Fig. 4 as *A*, *B*, *C* etc. for reference in the text, and where circled this denotes that the feature is shown in more detail in Figs. 5 onwards.

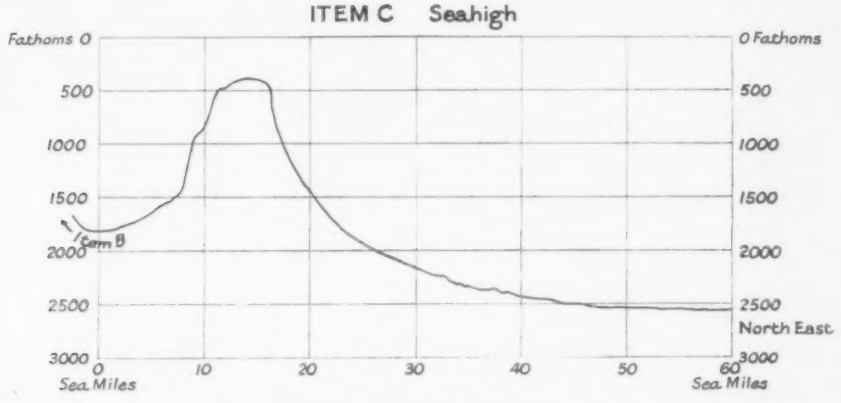

Fig. 5.

Unfortunately, there was no time available on passage along these profiles to investigate the interesting features encountered, thus only items *C* and *Q* can be clearly defined as table-mounts, but other sharp-topped features may have been profiles across the slopes of table-mounts. Item *B* is a bank and it seems likely that *G* may be a table-mount for it has a truncation or break-in slope near the summit. It is easy when looking at the single lines of soundings to believe one has a fuller picture than such a line justifies and the drawing of conclusions which would only be possible after a fuller survey has been resisted. Names of the underwater features used in the Figs. 1-4 are those recommended for the Pacific by the British National Committee on Ocean Bottom Features (WISEMAN and OVEY, 1955) with the exception of some additional names from current British Admiralty Charts and, in the vicinity of Fiji, those used by FAIRBRIDGE (1954). Depths below the surface are stated in fathoms but the height of a feature is given, such as that of a seamount or seascarp above the sea bed, in feet.

NARRATIVE

Profile 1

Leaving the Fiji Island Shelf the track led across a rough topography with an average depth of 1000 fathoms, which could be considered as a type of island borderland, until the declivity of the borderland *A* was reached at 13° 51′S., 176° 01′W. The sea bed fell steeply and in a space of 30 miles descended 12000, ft. As soon as the foot of this slope was reached the topography began to rise again to a "peak" at 1600 fm.

Here the ship moved down into a presumed volcanic district, the first positive feature of which was a small cone-shaped knoll. A second cone follows as the smooth plain of the archipelagic apron gradually rises towards a bank *B* and a table-mount *C*, *B* reaching 17 fm. A small coral sample was obtained from the top of *B*. The flat tops of these two features were between $3\frac{1}{2}$ and 4 miles across in the direction sounded. Small ripples, possibly indicating slumping, were clearly seen on the *E*/*S* trace at the foot of the feature *C*.

A smooth descent from *C* followed to a flat, featureless plain stretching about 50 miles before undulating topography was encountered and the ship passed from a volcanic district to a hill district.

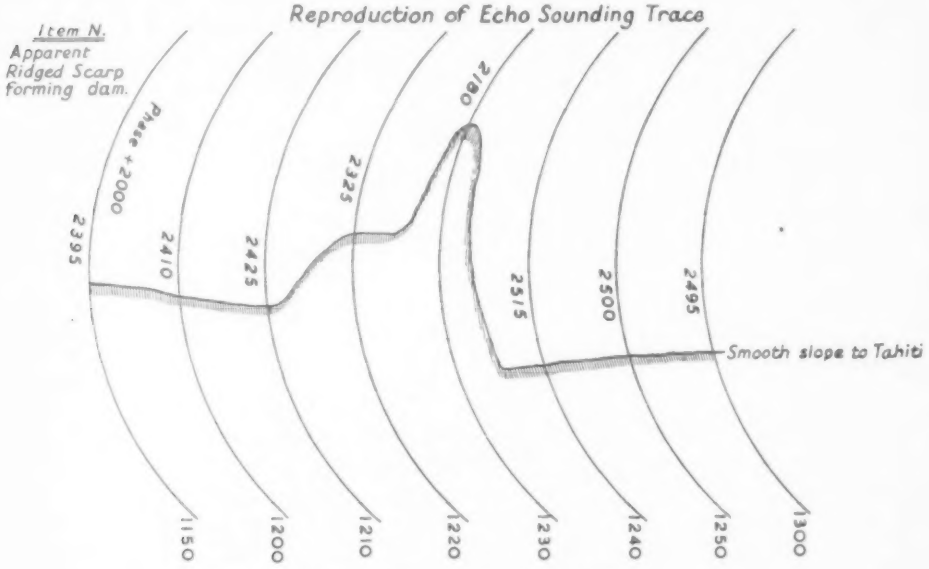

Fig. 6. Item N—Apparent Ridged Scarp.

For 350 miles this undulating sea bed gradually deepened from 2500 fm to 3200 fm and then rose more sharply for about 230 miles to form a large swell of just over 1000 fm depth. These features, *D* and *E*, are considered as a mountain district and contained two well-defined deep U-shaped depressions similar in shape to those described from the mid-Pacific by DIETZ *et al.* (1954). At one stage when descending the north-east side of this swell or mountain district there is a considerable escarpment when in 5 miles the depth increases 6500 ft.

Poor weather conditions ensued from the time of leaving the foot of the mountain district while the ship apparently traversed an undulating plain, with two V-shaped depressions, at 3000 fm depth gradually rising from 01° 41′S, 161° 55′W up the Christmas Island Slope which was interrupted by three cone-like features, *F*, *G* and *H*, before Christmas Island itself was reached. It is one of the largest existing islands of purely coral formation, being an atoll 35 miles long in the east-west direction by about 24 miles at its greatest width north-south. The whole Christmas Island Slope has been considered a volcanic district.

Profile 2

About 60 miles S.S.E. of Christmas Island, at the foot of the island slope, a smooth flat plain was reached over which the ship travelled for 60 miles before passing over two 9000 ft seahighs, *I* and *J* lying 40 miles apart, and of similar conical shape. South of these features the bottom was very rugged with small smooth " pocket " plains between the large features until a third 9000 ft seahigh, *K*, was reached 130 miles to the S.S.E. A similar rugged sea bed then continued to Malden Island.

Malden is a flat triangular coral atoll, 5 miles long from east to west. The island is girdled by a narrow fringing reef after which depths increase very rapidly.

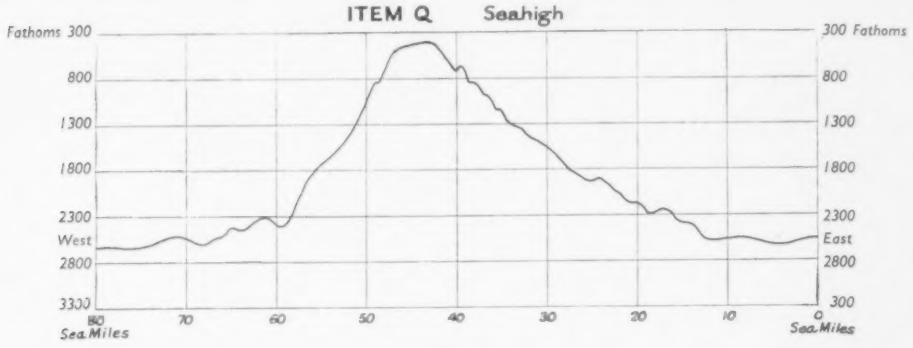

Fig. 7.

Within 110 miles S.S.E. from Malden there are three small features, probably volcanic, with typical smooth plains between them, after which the ship passed over an undulating plain for about 200 miles before entering a hill district which gradually assumed volcanic characteristics until the feature *L* was reached which indicated the ship passing about 10 miles west of Vostok Island, another low island of coral formation.

Flint Island 110 miles further S.S.E. was visited, it is low and flat with narrow fringing reef similar to Vostok and Malden. In fact the profiles obtained of both Malden and Flint are similar, the slope on the N.N.W. side having two or three presumed parasitic cones, whilst on the S.S.E. side the island slopes are practically featureless, terminating in flat smooth plains at a depth of just under 3000 fm. After 30 miles the volcanic-type plain merges into a hill district until about 200 miles N.N.W. of Tahiti when an apparent ridged scarp, item *N*, appears to form a dam for Tahiti's own archipelagic apron. The vertical face of this scarp of this apparent ridge is approximately 2000 ft high. But, whereas the faces and the lower levels of the two ridged scarps described by DIETZ *et al.* (1954) lie in the direction away from the major features of Hawaii and Bikini, in this case the face of the scarp and the lower level lie in the direction towards the major feature of Tahiti.

Tahiti itself is of volcanic formation having two main cones without parasitic cones either above or below the sea surface along the direction of the ship's track from the N.N.W. The highest summit on Tahiti is just over 7000 ft rising from a sea bed depth on its northern side of 2500 fm and thus giving a total relief to Orohena (the highest peak) of 22,320 ft.

Profile 3

On leaving Tahiti the ship's course was westerly across a smooth downward slope for about 100 miles to a depth of 2020 fm but interrupted by two seahighs, *O* and *P*, both coming within 500 fm of the sea surface.

Then the sea bed became more undulating, but more of a plain than a hill district, until a large 12,000 ft seahigh, *Q*, was reached and again coming within 500 fm of the sea's surface. This feature has a smooth, flattish top sloping towards the west and is about 4 miles across the top in the direction of the ship's track. It appears to lie about 50 miles in a direction 115° from the seahigh crossed by the Capricorn Expedition (1953) which rose to a depth of a little over 1000 fm. Thus at least two seahighs exist about 60 miles south of the low islands of Scilly and Mopelia.

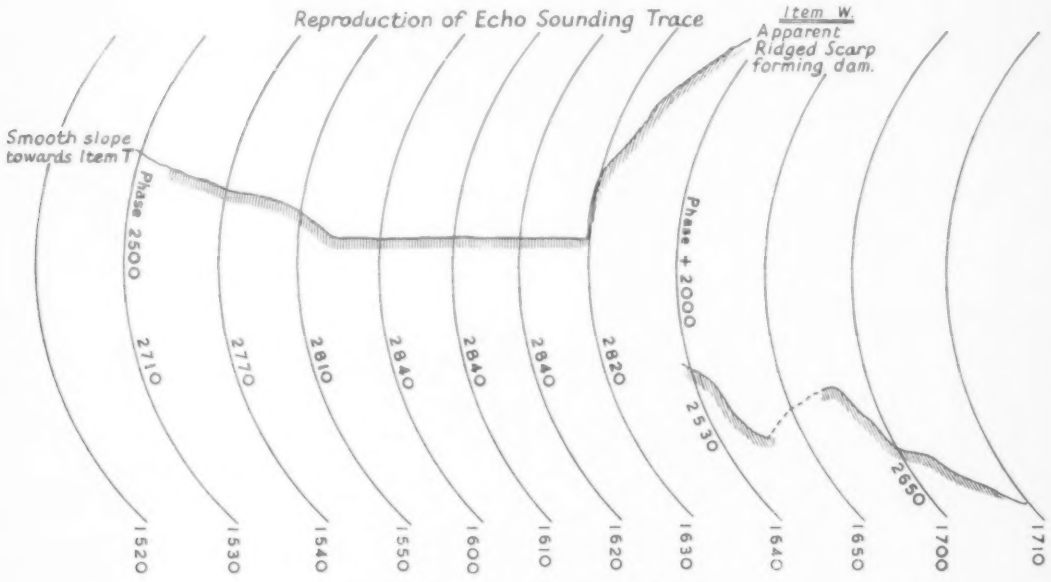

Fig. 8. Item W—Apparent Ridged Scarp.

A gently undulating plain was then crossed for about 400 miles, with but one noticeable feature about half-way across. This was unfortunately not recorded on the rising or eastern side due to a failure to phase the echo sounder in time.

The smooth slope running down the eastern side of Palmerston Island appears to be halted by a ridge which marks the western extremity of this plain district. Palmerston Island consists of six low sandy islets situated around the perimeter of an atoll about six miles in diameter and is in fact the top of a seamount 15,000 ft high. It has at least two parasitic cones on its western slope, the westward of which, *R*, is over 9000 ft high on its own.

From the foot of the Palmerston Slope a presumably volcanic plain runs westward for approximately 300 miles with at least two seahighs, *S* and *T*, rising from it. West of *T* the volcanic slope is terminated by an apparent ridged scarp. *W*, of similar height to the ridged scarp north of Tahiti, *N*, the vertical face being 2000 ft high. As at *N*,

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the ridged scarp leads to generally higher level of the sea bed as the ship steamed away from the major feature *T*.

The plain at a depth of 2500 fm to the westward of ridged scarp *W* begins, after 50 miles or so, to slope slowly away to the westward terminating eventually in the Tonga Trench. A greatest depth of 4885 fm depth was recorded on the echo sounder in the flat bottom of the Trench, *U*. Corrected by MATTHEWS (1939) tables, this depth would be 5144 fm and by KUWAHARA (1940) tables, 5149 fm. Depths shown in the figures are uncorrected.

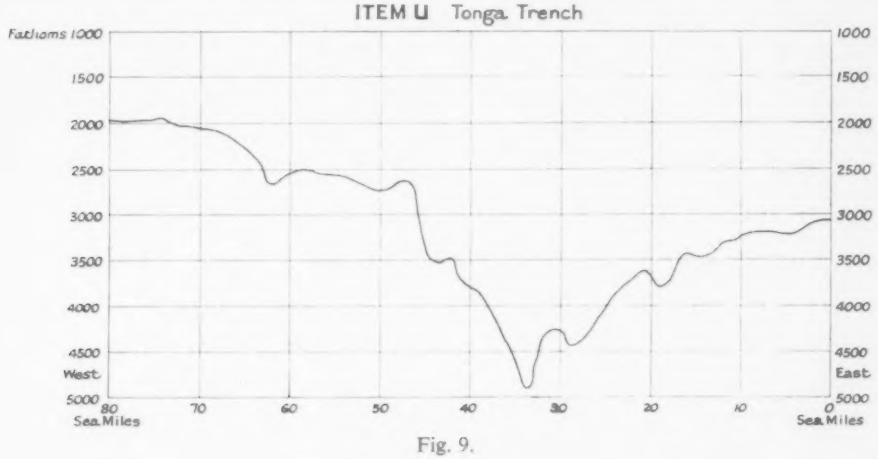

Fig. 9.

Table 1. *List of Seahighs.*

The following is a list of the more prominent seahighs passed over. Their geographical co-ordinates are given in the form proposed by WISEMAN *and* OVEY (1955)

Item	*Co-ordinates*	*Depth corrected by* MATTHEWS (1939)
Profile 1		
B	SW 1233–17422	17 fm (Bank)
C	SW 1213·5–17356·5	390 fm (Tablemount)
D & E	SW 0432·5–16501·5	1054 fm (Mountain District)
F	NW 0017–15952·5	1550 fm
G	NW 0125–15845	637 fm (Probably Tablemount)
H	NW 0153·5–15808	1049 fm
Profile 2		
I	SW 0013–15700	998 fm
J	SW 0053·5–15642·5	1060 fm
K	SW 0245–15551	960 fm
Profile 3		
P	SW 1742–15036	430 fm
Q	SW 1750·5—15404·5	415 fm (Tablemount)
R	SW 1804–16407·5	940 fm
T	SW 1813–16824	1540 fm (approx.)
Tonga Ridge	SW 1825–17419	98 fm

The profile obtained across the trench on an east to west course was 15 miles north of, and parallel to, the *Horizon* traverse C–C^1 shown by RAITT *et al.* (1955). It is, however, similar in shape to their B–B^1 traverse 30 miles to the north and showing

nothing of the northern slopes of Capricorn Seamount. As in *Horizon*'s B–B^1 section the shore wall (west) was found to be much steeper than the seaward wall. The two peaks occur towards the bottom of the trench on the eastern wall. After a steep rise on the western side of the trench for the first 15,000 ft the slope becomes more gentle, ascending towards the Tonga Ridge where a least depth of 98 fm was obtained.

The ship then passed into the Lau Basin, the floor of which appears to be a hill district.

Acknowledgments—I acknowledge the kind permission of the Royal New Zealand Naval Board to publish this paper although they do not necessarily agree with the views expressed. I wish to thank the Officers serving in H.M.N.Z.S. *Lachlan* in 1956 who watched over the echo sounder so carefully day and night. Special thanks are due to Lt. Cdr. W. J. DOOLE, R.N.Z.N. and Lt. (E) J. C. HARRISON, R.N.Z.N. for preparing the sounding plotting sheets. I also thank Mr. L. J. NEWELL of the Hydrographic Department, Admiralty, who prepared the line diagrams to illustrate this paper.

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A canyon-like feature in the Bay of Campeche

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(*Received* 12 *February* 1958)

Abstract—A previously unknown canyon bordering the Campeche Bank is described and delineated from new soundings obtained during a survey of the Southern Gulf of Mexico conducted in February, 1957.

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DURING February and March 1957, the Department of Oceanography and Meteorology at Texas A & M College conducted an expedition to the Bay of Campeche aboard the Research Vessel *A. A. Jakkula*. Approximately 1500 nautical miles of sounding track was accomplished. The bathymetric survey revealed the presence of a north-south trending canyon-like feature on the eastern side of the Bay of Campeche. The published charts of the area show no indication of this (see Fig. 1).

In addition to the bathymetry, 30 stations were occupied. Sediment cores were collected at 29 stations; with one exception all cores were taken by means of gravity coring devices. The cores ranged from 1 to 12 ft in length. Surface grab samples were collected with a Van Veen sampler on all continental shelf stations.

The survey ship was equipped with a continuous recording Edo Sonic Sounder, model AN/UQN 1B. This instrument was modified by the addition of a second keying device which permitted recording the outgoing signal at either the top or bottom of the paper, thus making it possible to record at all depths on the 600 fm scale. The modification is similar to that devised at the Navy Electronics Laboratory in San Diego, California (E. L. HAMILTON personal communication). The sounder was operated continuously while the ship was in the survey area.

All distances given in this paper are in nautical miles (1 nautical mile = 1·854 km). Depths are based on the standard vertical sounding velocity of 4800 ft/sec (1464 m/sec) and are uncorrected for variations in sound velocity. Navigation was by loran fixes, land sights on three occasions, and star positions. The navigation was checked by intersecting sounding lines. Except for one location these intersections were found accurate to within $\pm$ 2 miles.

It is proposed that the " canyon-like " feature to be described be termed Campeche Submarine Canyon. The axis of the Campeche Submarine Canyon lies along a line from 20° 00′N 92° 22′W to 21° 00′N 92° 42′W (see Fig. 2). It has a recognizable length of 85 miles and is 16 miles across at the central position. At the lower end it flares to a width of 30 miles. The canyon is still apparent in 600 fm as seen in profile D-D′ of Fig. 3. Due to unfavourable weather conditions at the time the survey vessel was in the area, it was not possible to delineate the canyon farther to the south-east or to make additional tracks parallel to the axis. At approximately 20° 09′N 92° 33′W a lobe of the canyon projects toward the south-west.

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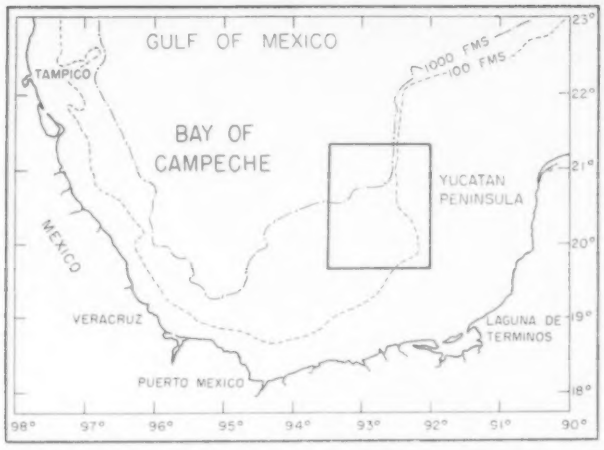

Fig. 1. Location of Campeche Submarine Canyon. Details of inset are shown in Fig. 2. Contours based on U.S.C. & G.S. Chart 1007.

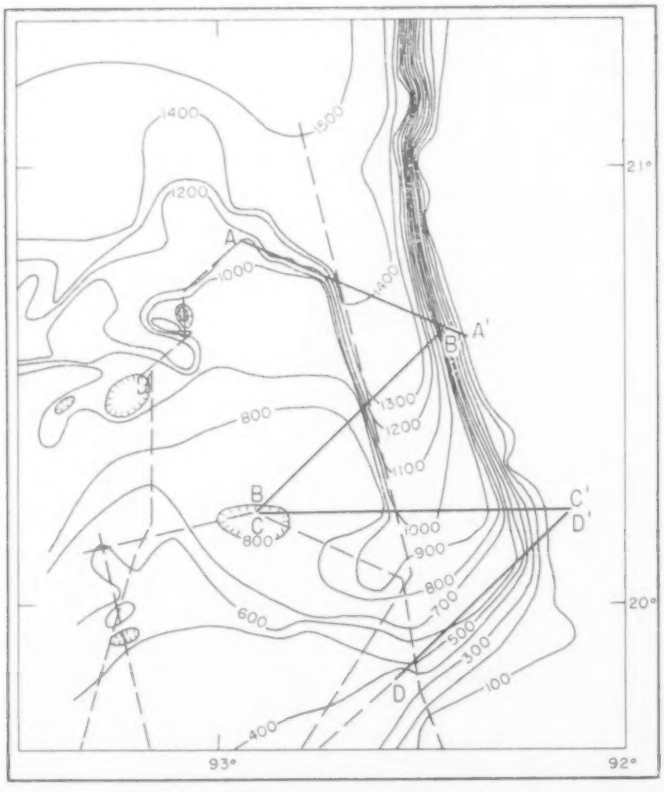

Fig. 2. Configuration of Campeche Submarine Canyon in the Eastern Bay of Campeche. (Contour interval = 100 fm ; 183 m.)

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The eastern wall near the central portion of the canyon has a slope of about 15° or 1400 ft/mile. This was determined from the contoured chart since there are no sounding lines normal to the slope. The slope of the western wall, in the same vicinity, is of the same order of magnitude. Down the canyon between the 700 and 1300 fm isobaths the slope is 1° 17′ or 118 ft/mile. The gradient changes to about 0° 17′ or 30 ft/mile between the 1300 and 1500 fm isobaths. Profile D-D′ shows the bottom to be relatively smooth and featureless. Profiles A-A′, B-B′ and C-C′ indicate that the canyon floor slopes from east to west with minor hummocks on the eastern side.

Details as to the possible origin of the canyon must be left until the study of the area is completed. However, a brief discussion of the geological setting is necessary. The Campeche Bank escarpment comprises the eastern wall of the canyon. This escarpment has been regarded as a tectonic feature by WEAVER (1950), PRICE (1951), LYNCH (1954) and others. However, from seismic evidence, EWING *et al.* (1955)

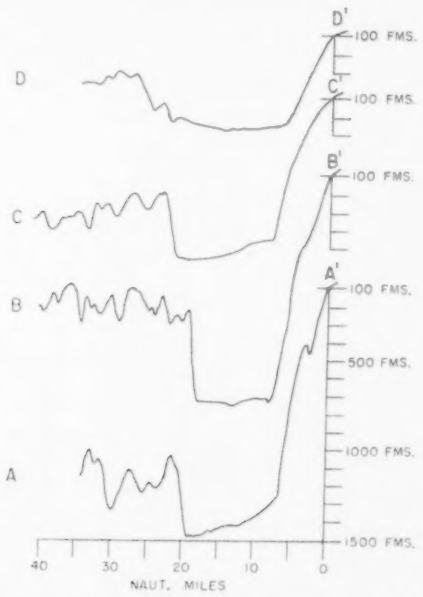

Fig. 3. Profiles of Campeche Submarine Canyon in the Eastern Bay of Campeche. (1 fm = 1·83 m ; 1 nautical mile = 1·854 km; vertical exaggeration X 25).

believe the southern Gulf to be a typical oceanic area, implying permanence. MILLER and EWING (1956), from magnetic evidence, suggest that the Yucatan Peninsula is a volcanic area covered by limestone, much like the Bahamas, rather than being due to faulting. The above references suggest conflicting views as to the extent of tectonic activity in this area.

The configuration of the western wall of the canyon could be ascribed to the front and eastern slope of a possible submarine delta. TAMAYO (1949) and PRICE (1951) have held that the large deltaic plain between Puerto Mexico and the Yucatan Peninsula indicates that the continental margins have been substantially projected seaward by sedimentation. If this is the case then the canyon could be due either to

depositional and/or erosional processes. The canyon floor may be an erosional feature modified by sedimentation or it may possibly reflect the original Gulf bottom.

There are also some shoreline features which may bear a relationship to this canyon. According to ING. G. SALAS of the University of Mexico (personal communication) the shoreline south of the canyon area has evidence of subsidence. Beaches are not prevalent and the sea is encroaching on the land as indicated by trees standing in the sea well out from shore. This is in contrast to the shore east of the Laguna de Terminos (see Fig. 1) which is composed of well-defined beaches and shore ridges as is the shore west of approximately 93° west longitude. This observation may suggest recent tectonic activity in the area.

We must conclude that the origin of this feature is not thoroughly understood. It may be structurally controlled and modified by both erosion and deposition.

Acknowledgments—Appreciation is expressed to R. G. BADER, M. A. HANNA, K. J. KOENIG, R. J. LEBLANC and G. RITTENHOUSE who critically read the manuscript and gave valuable suggestions. The cruise was supported, through the Texas A & M Research Foundation, by the Office of Naval Research under Contract N7onr-48702 (Project NR 083 036) and was a co-operative venture with scientists representing the Mexican government. The laboratory work was supported in part by the United Gas Pipeline Company, and in part by Research Grant NSF-G5039 of the National Science Foundation.

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Maxima in the vertical distribution of particles in the sea

N. G. JERLOV

(*Received* 25 *March* 1958)

Abstract—The presence of maxima in the vertical distribution of particulate matter in the sea is discussed and interpreted. Below the euphotic zone the mechanism at which a maximum is formed requires that the sinking particles are slowed up and that the eddy diffusion increases towards greater depths. The particle content in the deep sea is on an average proportional to the abundance in the upper layers of the water region. The particle distributions are much controlled by eddy diffusion and so by flow of water masses. Thus it is shown for a number of stations and sections in the oceans that a clear relationship between particle distribution and salinity distribution exists, implying that particle maxima occur in the core of the water mass.

INTRODUCTION

THE most obvious results obtained by particle measurements during the Swedish Deep-Sea Expedition have already been discussed (JERLOV, 1953). The discussion has essentially been confined to particle distributions in the upper illuminated strata and to distributions influenced by the proximity to bottom or to land. There is, however, much more information concealed in these Tyndall data. The presence of particle accumulations frequently found at different levels in the sea obviously has some bearing on the stratification of the water masses.

Using the Tyndall values obtained by the Swedish Deep-Sea Expedition (BRUNEAU *et al.* 1953) an attempt is made here to find some systematic order in the vertical distributions and to examine more closely the occurrence of particle maxima. As to the adequate denomination it is suggested that such a particle maximum should be called *optical scattering layer* in analogy to sonic scattering layer.

THEORETICAL BACKGROUND

The particle distribution is controlled by different factors the interrelation of which is rather intricate. From the expression for the distribution of a non-conservative concentration a mathematical model considering vertical gradients only in the steady state is obtained

$$A \frac{\partial^2 s}{\partial z^2} - \left(v - \frac{\partial A}{\partial z} \right) \frac{\partial s}{\partial z} - \frac{\partial v}{\partial z} s + R = 0 \qquad (1)$$

with the following designations

s = particle concentration; z = depth directed positively downwards; R = local time change of particle concentration ; v = vertical sinking velocity ; A = eddy diffusivity.

The positive quantities s, v and A are functions of depth only. The factor R is controlled by biological processes and is either positive or negative.

Any exact interpretation of equation (1) with respect to the total amount of particles is not possible since the change of v and R with depth is incompletely known. It is obvious that the mechanism by which a particle accumulation is established in the

sea can be studied only in a qualitative way. A general conception may be approached by examining some simplified cases.

(1) RILEY, STOMMEL and BUMPUS (1949) have considered the distribution of phytoplankton in a two-layered system in a bottomless sea. They introduce the quantity ω as the production rate coefficient and put the actual rate of production $R = \omega s$. The upper layer corresponding to the euphotic zone is characterized by a constant production rate coefficient ($\omega > 0$), the lower layer by a constant negative one ($\omega < 0$). If the sinking velocity v and the coefficient of eddy diffusion A are assumed to be constant, equation (1) is reduced to the formula

$$A \frac{\partial^2 s}{\partial z^2} - v \frac{\partial s}{\partial z} + \omega s = 0 \tag{2}$$

Their solution of equation (2) shows that a maximum is developed near the lower limit of the euphotic zone, the more pronounced, the lower the eddy diffusion is. The practical tests of this method have been reasonably successful for tropical regions where small seasonable departures from the steady state appear. The model though over-simplified is most instructive in demonstrating that an exact relationship among the factors controlling the phytoplankton distribution can be found. The point is stressed that the distribution mentioned is obtained without assuming increased stability or reduced sinking velocity.

In the coming discussion it is postulated that the existing maximum is of such a character that the following scheme is valid.

	$\frac{\partial^2 s}{\partial z^2}$	$\frac{\partial s}{\partial z}$
above the maximum	> 0	> 0
in	< 0	$= 0$
below	> 0	< 0

(3)

It is readily seen that equation (2) agrees with a maximum according to this presumption if

in the maximum	$\omega > 0$
below	$\omega < 0$

So it is probable that the maximum occurs at the lower limit of the euphotic zone.

(2) A better approach to representing distributions during the production season, when a thermocline is created, is to treat the eddy diffusion as a function of depth. The euphotic zone only is considered ($R > 0$). Though the sinking particles are to some degree slowed up in the discontinuity layer, a constant value of v is reckoned with for the sake of simplicity. Hence

$$A \frac{\partial^2 s}{\partial z^2} - \left(v - \frac{\partial A}{\partial z} \right) \frac{\partial s}{\partial z} + R = 0$$

According to the premises (3) the existence of a maximum requires that

above the maximum	$\frac{\partial A}{\partial z} < v$

below $$\frac{\partial A}{\partial z} > \nu > 0$$

This is consistent with the general distribution features of A which show a minimum in the thermocline region.

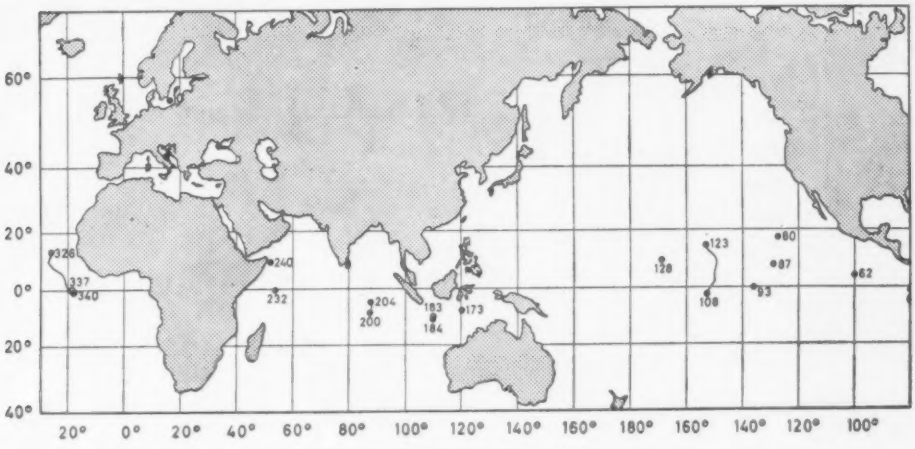

Fig. 1. Stations and sections.

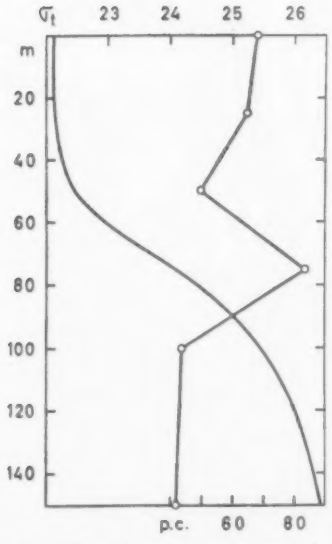

Fig. 2. Particle accumulation in the discontinuity layer at Station 62 in the Pacific.

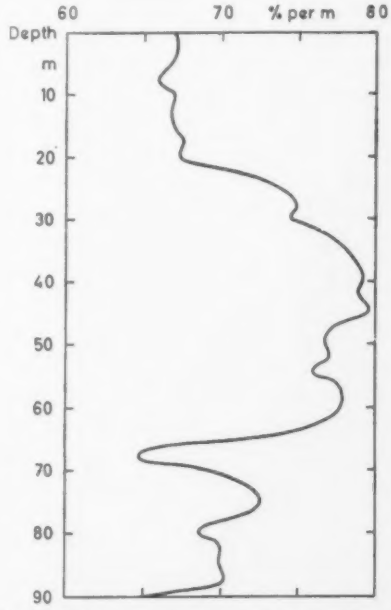

Fig. 3. Transparency curve for Station 10 (Swedish Station made in 1937) in the Baltic in August 1937.

RILEY *et al.* have also calculated the distribution of phytoplankton in the euphotic zone with respect to all environmental data and found that the maximum quantity

of phytoplankton occurs about midway between the depth of the greatest stability and the compensation depth.

These arguments go to prove that the mechanism at which a particle accumulation is formed in the euthotic zone implies that the eddy diffusion is intensified downwards from the maximum. It follows that the maximum should be best developed when the discontinuity layer is near the lower limit of the euphotic zone. Such a situation is frequently encountered in coastal as well as in oceanic areas. As an instance density and particle distribution – the latter from Tyndall measurements – for Station 62 in the eastern Pacific (see map in Fig. 1) are depicted in Fig. 2.

(3) The next step would be to consider the fate of the sinking particles and their distribution below the euphotic zone. The essential thing is that consumption of the particulate material takes place ($R < 0$). The effect of a deep boundary layer on the distribution is illustrated by a concrete situation at Station 10 in the South Baltic where a sharp halocline (0·5‰ per m) occurs at 60-80 m. The bottom water is here stagnant for long periods. The transparency curve in Fig. 3 obtained in August 1937 by means of a 2 m transparency-meter exhibits a salient minimum at the salinity discontinuity layer at 67 m due to a considerable particle accumulation.

From equation (1) it is found that in the maximum

$$A \frac{\partial^2 s}{\partial z^2} - \frac{\partial v}{\partial z} s + R = 0$$

which, as

$$\frac{\partial^2 s}{\partial z^2} < 0,$$

means that

$$\frac{\partial v}{\partial z} < R/s < 0$$

In this case the pre-requisite for a maximum is that the sinking particles are slowed up in the region of the halocline, in the first place on account of the downwards increasing density of the water. Probably an appreciable amount of light and small-sized organic matter is definitely stopped in the boundary layer where it is subjected to a gradual decomposition.

(4) The preliminary views presented may provide some basis for the discussion of particle distribution in the deep sea as studied by Tyndall measurements. A significant factor is the change with depth of the vertical sinking velocity v. This is determined primarily by the size of the sinking particles. The size decreases by decomposition of particles, chiefly down to 1000 m, which reduces the average rate of sinking. Even if the organic part of the individual particle is decayed so that its gravity increases, the reduction in size will become the predominating effect leading to a lower sinking rate according to Stokes' law. Furthermore there is the general tendency of retardation of sinking due to increase of water density and of viscosity downwards. This implies that we can safely assume the term $\partial v/\partial z$ to be negative.

The factor R takes negative values in the deep sea. Our knowledge of the marine organic consumption is however rather limited. The fundamental process is the bacterial activity which is reduced downwards and manifest in diminished oxygen consumption. Grazing is believed to play a minor role.

As a typical instance of particle distribution in the deep strata the distribution in a meridional section near 150°W in the Pacific will be closely examined. A conspicuous

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maximum occurs between 700 and 800 m at all stations in this section. Fig. 4 shows mean values of particle content and of salinity. It is seen that the particle maximum coincides with the salinity minimum.

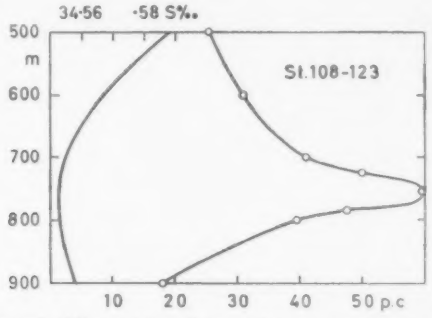

Fig. 4. Particle maximum coinciding with salinity minimum at 760 m. Mean values for section 108-123 in the Pacific (See also Fig. 12).

It must be observed that the Tyndall data are in a unit proportional to the total particle surface per volume unit (JERLOV, 1955). For the sake of simplicity the denomination " particle content " is used for the values. In order to convert them into mass concentrations the reduction in particle size with increasing depth must be known but this information is at present beyond our grasp. Generally speaking, towards greater depths the increase of particle mass is slower than the gradients of the Tyndall result indicate whereas the decrease is more rapid.

As regards the maximum at 755 m in Fig. 4 it represents undoubtedly also a maximum in mass concentration.

As in Section (3) the basic test is that in the maximum $\partial v/\partial z < R/s < 0$.

There is no adequate ground for assuming that the rate of sinking would be less reduced below the maximum. On the other hand consumption is likely to decrease towards deeper layers. Therefore it is plausible that $\partial v/\partial z < R/s$ also holds true below the maximum. Then it follows that

$$\frac{\partial A}{\partial z} > v > 0$$

The formation of a maximum in the deep sea is thus attributed to retarded sinking of particulate matter as well as to increase of eddy diffusion towards greater depths.

DEFANT (1941) has shown that the diffusion at the spreading of the Antarctic Intermediate Water in the Atlantic attains a minimum at the boundaries whereas a maximum occurs 150 m below the salinity minimum. There is reason to believe that a similar mechanism is active at the spreading of the low-salinity water in the Central Pacific so that the requirement $\partial A/\partial z > 0$ could actually be fulfilled in the interval 500-900 m.

The mechanism with retarded sinking should imply that a certain amount of the fine particulate material is arrested at 750 m where particles are suspended in the full sense of the word. However, the limitations with a model of vertical transport only for explaining the presence of particle maxima must be borne in mind. The significant change of eddy diffusion with depth is effected by the flow of the water masses. This brings us to the question of horizontal transport.

HORIZONTAL TRANSPORT

The main supply of particles to the sea is maintained by organic production through photosynthesis in the upper illuminated layers. In addition terrigenous material is brought to the sea by land drainage or by winds. In particular, distributions near land are influenced by drift of surface water from rivers. As an illustration the particle content at Station 21 in the Adriatic Sea is shown in Fig. 5. Besides the usual particle maximum in the thermocline region an accumulation of river material occurs at 5 m originating chiefly from the Po.

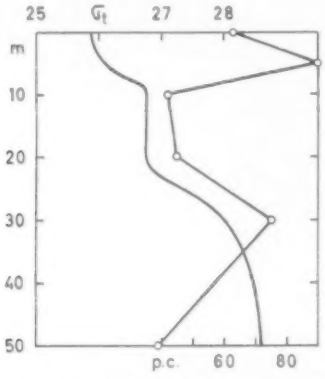

Fig. 5. Particle accumulation in the surface layer due to transport of river material. Station 21 in the Adriatic Sea in August 1955. Station occupied on Italian-Swedish Expedition in 1955. Data not yet published elsewhere.

In the deep sea the flow of the water masses is the agency for horizontal transport of particulate material. This should not be understood in such a way that particles are carried with the water mass from its " birth-place." Instead, during its flow, the water mass is incessantly supplied with particles sinking from the euphotic zone.

PARTICLE DISTRIBUTION AND WATER MASSES

It may be gathered that the particle content in the deep sea is on an average proportional to the abundance in the upper layer of the water region. The particle distribution is much controlled by eddy diffusion and thus by flow of water masses. In other words, the distributions should reflect the stratification of the water masses. In order to interpret this assumption, Tyndall data will be discussed for localities where well-defined water masses occur.

The question arises how to illustrate the particle distributions. Though it is often adequate to give the particle content as a function of depth, a representation by plotting against temperature, which is in analogy with *TS*-diagrams, is usually to be preferred.

The Atlantic Ocean. It must be admitted that the significance of particle maxima in the sea was not fully realized when the experiments were conducted, and the research was not consistently aimed at relating particle distribution to the structure of water masses. As regards the Atlantic Ocean it must be taken into account that disturbances in distribution may arise by lateral transport of material from the Mid-Atlantic Ridge (JERLOV, 1953).

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A vertical section between the Cape Verde Islands and the Romanche Deep – unfortunately not extended to greater depths – is shown in Fig. 6. There are clear indications at some stations that high particle concentrations appear at the 5°–6° levels where the salinity minimum of the Antarctic Intermediate Water is encountered.

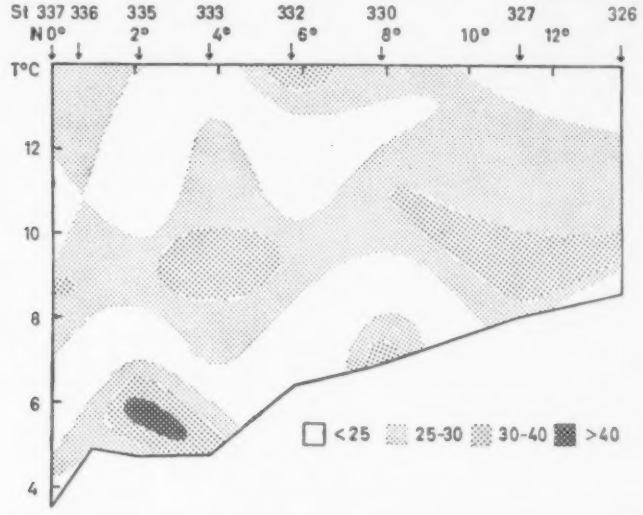

Fig. 6. Vertical distribution of particles at temperature levels between Stations 326 and 337 in the Atlantic.

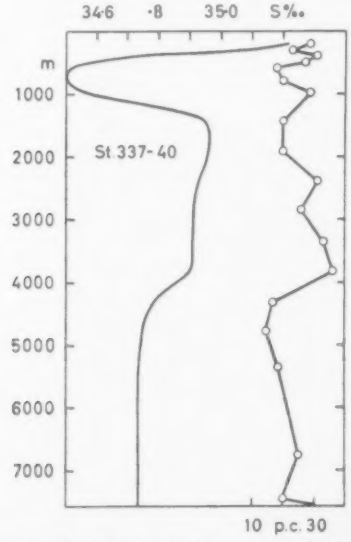

Fig. 7. Particle stratification compared with the salinity curve at the Romanche Deep (Station 337-40).

Furthermore the South Atlantic Central Water present at levels of 9°–10° is characterized by particle maximum at all stations. In these cases particles are accumulated in the core of the water mass which bears reference to the typical distribution in the Pacific already discussed.

It is relevant in this connexion to examine more closely the particle stratification at the Romanche Deep. The two maxima mentioned are not very conspicuous, occurring at 400 m and 1000 m respectively (Fig. 7). The latter is thus somewhat below the salinity minimum in the Antarctic Intermediate Water. The distribution curve exhibits another salient feature in the marked decrease in particle content just below 4000 m. Cold Antarctic Bottom Water from the Brazilian basin flows over the sill depth at 4100-4400 m and mixes with the North Atlantic Deep Water (BÖHNECKE, 1927). Thus the deep water is poor in particles but this is not everywhere in the Atlantic a typical property of the Antarctic Bottom Water. As mentioned, the interpretation of distributions in the deep Atlantic water is obscured as it is difficult to judge to what extent the formation of a maximum is influenced by topographical features.

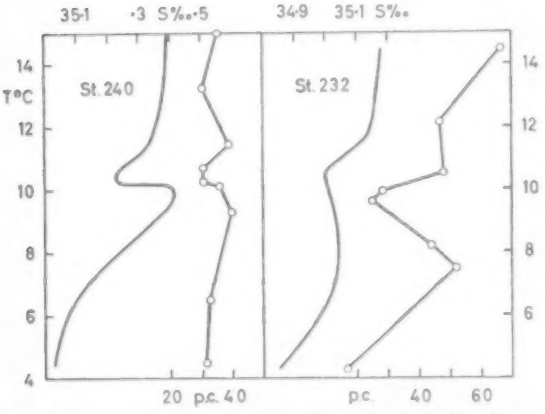

Fig. 8. Spreading of the Red Sea Water in the Indian Ocean indicated by particle maxima as well as by salinity maxima (at 8°–10°).

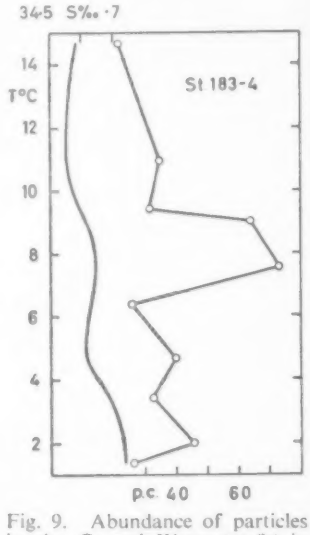

Fig. 9. Abundance of particles in the Central Water (at 8°) in the Java Trench.

The Indian Ocean. Generally speaking the Indian Ocean presents well-developed stratification of particulate matter. As a first instance it is relevant to consider the spreading of the Red Sea Water. Station 240 is at 10° N near the Gulf of Aden, Station 232 southwards at the Equator (Fig. 8). It may be recollected that in these areas the Antarctic Intermediate Water characterized by a salinity minimum is lifted to a temperature level of 10° by the underlying high-salinity Red Sea Water (THOMSEN, 1933). In these diagrams the striking congruity between *TS*-curve and *Tpc*-curve is apt to convince one of an existing relationship implying that the particle distribution is largely controlled by the flow of the water masses. As it spreads in the Indian Ocean the Red Sea Water thus attracts particulate matter on account of the vertical variations in eddy diffusion. At Station 232 where the content of particles is high in the upper strata this accumulation is very pronounced.

Another type of *TS*-diagram applies to the eastern areas of the Indian Ocean which are here represented by Station 183-4 in the Java Trench (Fig. 9). There is only a slight maximum in the Antarctic Intermediate Water of 5° temperature whereas

the Central Water of about 8° is overwhelmingly rich in particles. This may be due to a fairly high plankton population in the surface water, but evidently also to a conjunction of favourable factors for forming a maximum. Such an intense stratification was also encountered at the adjacent St. 190.

In the region to the west the picture is rather similar as appears from a vertical meridional section from 11°–6·5°S, near 88°E (Fig. 10). The Central Water and the Intermediate Water are nicely reflected as bands of particle accumulations. Farther northwards in the section the salinity maximum becomes more diffuse and the associated particle maximum is totally absent.

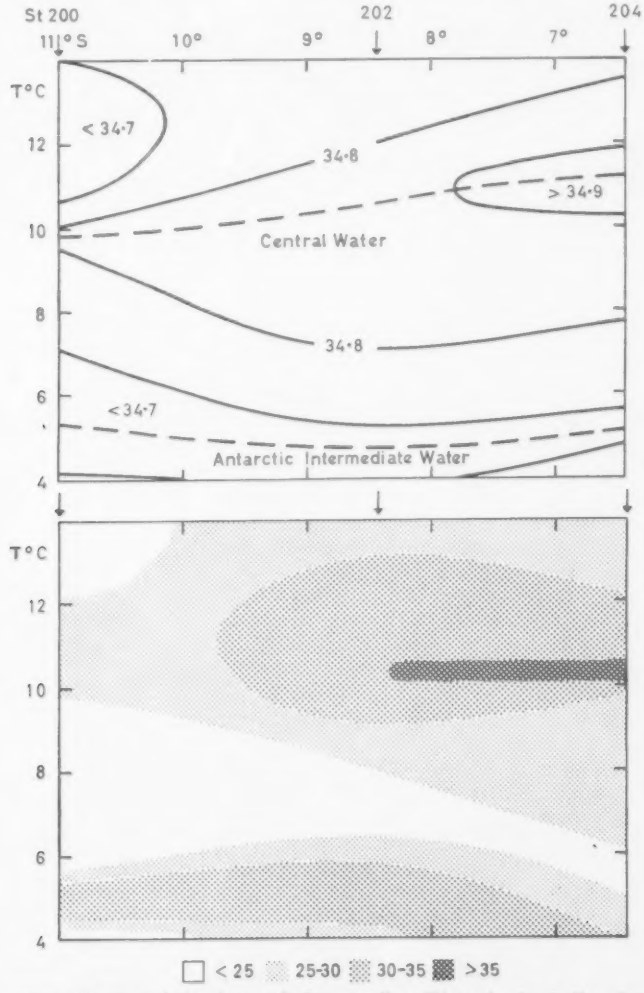

Fig. 10. The Central Water and the Antarctic Intermediate Water in the Indian Ocean reflected as bands of particle accumulation.

The Pacific Ocean. A distribution from the Flores Basin may here be adduced to show that the particle content is in some cases a typical property of the water

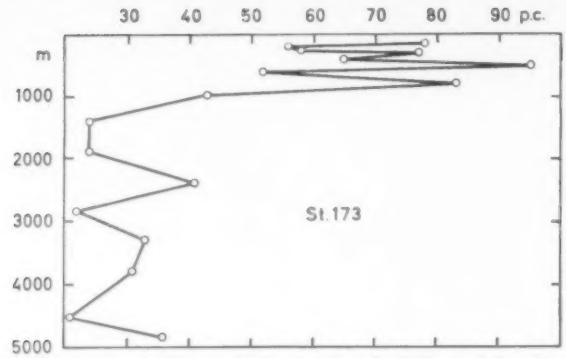

Fig. 11. Particle stratification in the Flores Basin showing the inflow of clear Pacific Water between 800 and 1400 m.

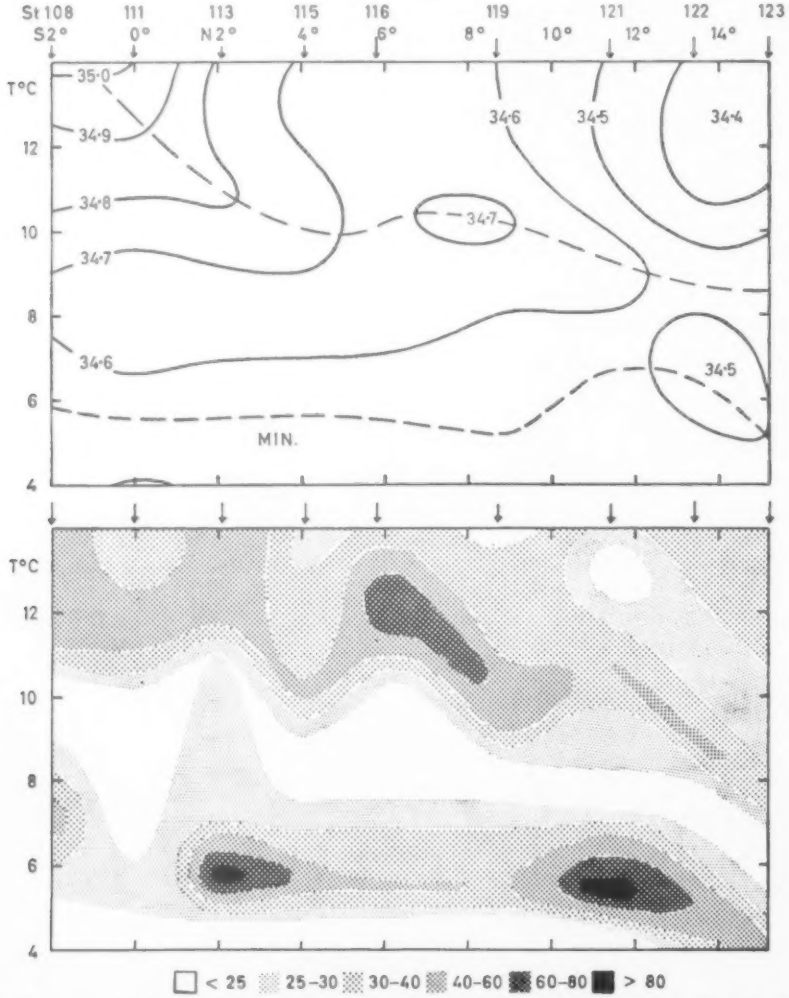

Fig. 12. Stratum with high particle concentration in the salinity minimum (see also Fig. 4). Tongue of high-salinity water from the subtropical convergence also rich in particles. Pacific section 108-123.

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mass and may serve to distinguish it. Station 173 in Fig. 11 exhibits an abundance of debris with a marked stratification in the upper layers. A conspicuous decrease in particles between 800 and 1400 m suggests the inflow of clearer water from the Pacific passing over the different sill depths to the basin.

The Pacific section, for which the mean distribution has already been discussed, merits some further attention (Fig. 12). One may ask whether such a stratum of particles in the salinity minimum is characteristic of the whole Pacific. There are certainly indications of a maximum at other localities but the phenomenon is by far best developed in the central regions of the Pacific. This is probably due to the slow circulation and the low turbulence in the central areas.

Another detail in the picture may be pointed out. The penetration of high-salinity water from the subtropical convergence is rather dominating. In particular between 6° and 10°N a tongue of particle-rich water is present which conforms to this flow. This produces more evidence to the general tendency of particle accumulation in the core of the penetrating water mass.

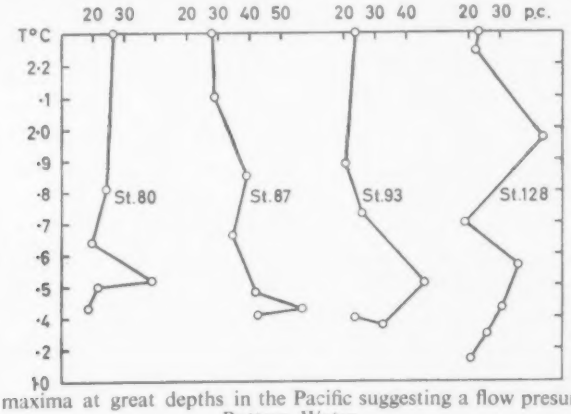

Fig. 13. Particle maxima at great depths in the Pacific suggesting a flow presumably of Antarctic Bottom Water.

Certain difficulties are involved in the interpretation of particle data from great depths in the ocean. The suspicion is entertained that the stratification may be affected by lateral distribution from topographic highs. Some stations in the central Pacific, however, seem to be safe from such influence. Stations 80, 87, 93 and 128 all happen to be stations where samples were taken every 500 m, and they are thus not selected. It is noted in Fig. 13 that a salient maximum appears at 1·4°–1·6°. There is no variation in salinity to indicate a flow at these levels. But the particle distribution suggests that the diffusion is changed with depth in such a way that one is inclined to trace a flow presumably of Antarctic Bottom Water. It is possible that the particle distribution in some cases is the more sensitive means of distinguishing features in the circulation.

DISCUSSION

So far nothing has been said about the influence of animal life on particle content. Though a redistribution of particles due to animals occurs, the rate of grazing seems to be so moderate (RILEY *et al.*) that any drastic change in the vertical distributions is not likely to take place.

One may venture to assert that in many cases the attempt to bring some systematic order in the apparently confusing multitude of Tyndall data has met with some success. Naturally there are also instances for which one fails to find any relationship. It must be born in mind, however, that the measurements could have missed some maxima between the levels where samples were taken. It seems established that there is often an indisputable relationship between particle distribution and salinity distribution inasmuch as particle distribution is much controlled by the turbulence and ultimately by the flow of the different water masses. As our knowledge of the rate of decomposition, the sinking of particulate matter in the sea and of the vertical diffusion pattern is rudimentary, this examination must be considered as a first approach to the problem.

It is beyond the scope of this report to discuss the distribution of chemical properties and their relation to the particle content. It may be stated briefly that particle maxima down to 1000 m are often associated with maxima in phosphate, less often with maxima in carbon dioxide. The oxygen minimum layer is usually encountered somewhat above the particle accumulations. On the other hand it is established that particles in the deep sea serve as adsorption nuclei for phosphate and for bacteria. The circumstance that radioactive substances are also adsorbed on the particulate matter has lately aroused a new interest.

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The accuracy of wave measurements made with vertical accelerometers

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(*Received 4th April* 1958)

Abstract—This paper examines theoretically the errors introduced into wave measurement by using an accelerometer which sets itself into the " apparent vertical," that is, perpendicular to the local water surface, instead of being stabilised to measure the true vertical acceleration. The spectrum of the error signal in terms of wave height rises steeply at low frequencies, and although the errors do not seriously affect the main wave components, bands of low swell may be obscured under certain conditions.

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INTRODUCTION

WAVE measurement on the deep sea is complicated by the absence of an accessible fixed reference level. Some instruments have been described which overcome this difficulty by measuring the vertical component of the acceleration of a buoy or a ship and integrating this twice electronically (TUCKER, 1956 and DORRESTEIN, 1957). In principle this system requires the accelerometer to be stabilised in direction so that the true vertical component of acceleration is measured, but in practice this involves considerable complication and expense and the two instruments referred to above, both measure the resultant acceleration, that is, the magnitude of the vector sum of gravity and the wave acceleration (which includes a horizontal component). This introduces errors which are examined below. The problem is of considerable importance since the use of accelerometer buoys promises to be one of the principal methods for measuring waves on the deep sea, and several laboratories are developing instruments of this type.

The direction of the resultant acceleration is termed the apparent vertical and is the direction in which a short-period pendulum will set itself. Also, it is a fundamental property of a free, constant-pressure fluid surface that it is perpendicular to the direction of the apparent vertical as measured by an instrument moving with the fluid particles.

The resultant acceleration may thus be measured by an accelerometer mounted either on a short-period pendulum or on a flat float which sets itself in the water surface.

A brief account of these errors has been given by TUCKER (1956). They will be examined here in more detail, and in particular the spectrum of the errors will be considered.

SYMBOLS

$|G(t)|$ = magnitude of resultant acceleration due to the combination of gravity and the wave acceleration

$|H(t)|$ = magnitude of the horizontal component of the acceleration of the accelerometer

$I(t) = |G(t)|$ minus the true vertical acceleration
g = acceleration due to gravity
x, y = horizontal co-ordinates
z = vertical co-ordinate
} of the accelerometer
$\ddot{x}$ = etc. are second time derivatives
$\mu = 2\pi \times$ frequency of a component of the wave pattern
$\mu_1 = 2\pi \times$ frequency limit of response of the buoy
$\sigma = 2\pi \times$ frequency of a component of the error signal
$S(\mu)\, d\mu$ = mean square wave amplitude in a range of angular frequencies μ to $\mu + d\mu$
$S(\mu)$ = is termed the spectral density of z
$S(\mu, \theta)$ = the two-dimensional spectral density
$w(\mu)$ = spectral density of $|H(t)|$
$W(\sigma)$ = spectral density of $I(t)$
$E(\sigma)$ = spectral density of $\int\int I(t)\, dt^2$
k, m, n, p, q are integers
v = wind velocity
ϕ = a random phase angle
θ, ψ are directions of approach of wave components
α_n, β_n are the amplitudes of the cosine and sine components of the n^{th} angular harmonic of $S(\mu, \theta)$
$P = \alpha_2/\alpha_0$
$Q = \beta_2/\beta_0$
$R = \sqrt{\alpha_2^2 + \beta_2^2}/\alpha_0$ = amplitude of 2nd harmonic of angular distribution relative to the total energy

THEORY

The magnitude of the resultant acceleration due to the combination of gravity and the wave accelerations is given by

$$|G(t)|^2 = (g + \ddot{z})^2 + \ddot{x}^2 + \ddot{y}^2 \tag{1}$$

Expanding the square root of the right-hand side

$$|G(t)| = g + \ddot{z} + \frac{\ddot{x}^2 + \ddot{y}^2}{2g} - \frac{\ddot{z}(\ddot{x}^2 + \ddot{y}^2)}{2g^2} + 0\left(\frac{\ddot{x}^4}{g^3}\right) \tag{2}$$

Now $\ddot{z}/g$ never exceeds 1 and is usually considerably less, and the maxima of $\ddot{z}$ and $(\ddot{x}^2 + \ddot{y}^2)$ occur at different times. The 4th and subsequent terms on the right-hand side of equation (2) are therefore small compared with the 3rd and will be neglected. Thus,

$$I(t) \simeq (\ddot{x}^2 + \ddot{y}^2)/2g = |H(t)|^2/2g \tag{3}$$

For the present purposes the spectrum of $I(t)$ is required.

According to first-order theory, any wave system on the surface of deep water may be represented by the sum of an infinite number of elementary sinusoidal wave trains, each of which on its own would cause the water particles to move in a vertical circular orbit with constant angular velocity. The phases of these elementary com-

ponents is random, and the result of their superposition gives a random Gaussian process. Though careful measurement of steep seas sometimes shows a significant departure from the Gaussian distribution, it has been found to be an adequate approximation for nearly all practical purposes and will be assumed here.

The spectrum of $I(t)$ will first be derived on the assumption that all the elementary wave trains travel in the same direction, since this is a comparatively simple analysis and shows the principles of the method more clearly. An expression for the spectrum of $I(t)$ will then be derived for the general case in which the component wave trains may come from any direction.

UNIDIRECTIONAL WAVE SYSTEM

It will be apparent that if all the elementary wave trains travel in the same direction, the spectrum of $H(t)$ is the same as the spectrum of $\ddot{z}$, and that $H(t)$ is also a random Gaussian quantity. RICE (1945) has considered the spectrum of a signal which is the square of such a quantity, and applying his result to equation (3) gives

$$W(\sigma) = \frac{1}{4g^2} \int_{-\infty}^{\infty} w(\mu)\, w(\sigma + \mu)\, d\mu \tag{4}$$

Here it is taken that $w(\mu) = w(-\mu)$

and $\sigma \neq 0$

Writing $$z = \sum_n c_n \cos(\mu_n t + \phi_n)$$

then $$\ddot{z} = -\sum_n c_n \mu_n^2 \cos(\mu_n t + \phi_n)$$

It follows that $$w(\mu) = \mu^4 S(\mu) \tag{5}$$

and by similar reasoning

$$W(\sigma) = \sigma^4 E(\sigma) \tag{6}$$

Equation (4) therefore becomes

$$E(\sigma) = \frac{1}{4g^2 \sigma^4} \int_{-\infty}^{\infty} \mu^4 S(\mu)\, (\sigma + \mu)^4 S(\sigma + \mu)\, d\mu \tag{7}$$

In order to solve this equation, it is necessary to assume a wave spectrum $S(\mu)$. Three formulae for the wave spectrum have been proposed, and though often called "theoretical" formulae, they are in fact all largely empirical. They have been compared by NEUMANN and PIERSON (1957). Unfortunately, they differ greatly at high frequencies, which are particularly important in the present application owing to the factors μ^4 and $(\sigma + \mu)^4$ inside the integral in equation (7). At high frequencies, Darbyshire's spectrum varies as $1/\mu^7$, Neumann's as $1/\mu^6$, and the Roll Fischer spectrum as $1/\mu^5$. The evidence from practical spectra at high frequencies does not seem to be adequate to choose between these forms, and it has therefore been decided to use NEUMANN's spectrum here as the best compromise.

NEUMANN's spectrum is

$$S(\mu) = \frac{C}{2\mu^6}\, e^{-2g^2/\mu^2 v^2} \tag{8}$$

where C is a constant $= 4{\cdot}80 \times 10^4$.

If it is assumed that the wave-measuring buoy responds fully to frequencies up to μ_1, and has zero response for higher frequencies, equation (7) becomes

$$E(\sigma) = \frac{C^2}{16\, g^2\, \sigma^4} \int_{-\mu_1}^{\mu_1} \left[\frac{1}{\mu^2}\, e^{-2g^2/\mu^2 v^2}\right]\left[\frac{1}{(\mu+\sigma)^2}\, e^{-2g^2/(\mu+\sigma)^2 v^2}\right] d\mu \tag{9}$$

The author has not been able to solve this equation analytically, and has therefore solved it by numerical integration for three different values of v.

The frequency cut-off was taken as approximately 1 c/sec, but this is not at all critical, and even if the sum were taken to infinite frequency, the spectral densities $E(\sigma)$ would be increased by only about 10 per cent.

The results are shown graphically in the figure.

TWO-DIMENSIONAL WAVE SPECTRUM

In the general case when the waves are coming from a wide range of directions, the spectrum of $|H(t)|$ will not be the same as that of $\ddot{z}$.

It will again be assumed, as discussed above, that the wave pattern may be considered as the sum of a large number of elementary wave trains which will be taken to have frequencies separated by a constant small interval $\Delta\mu$ and to be travelling in directions separated by a constant small angle $\Delta\theta$. These intervals will later be taken to be infinitely small to give a continuous spectrum in the usual way.

Thus

$$\left.\begin{aligned}
\ddot{x} &= \sum_{m=1}^{\infty} \sum_{p=1}^{2\pi/\Delta\theta} \mu_m^{\,2}\, c_{mp} \cos p\Delta\theta \cos(mt\,\Delta\mu + \phi_{mp}) \\
\ddot{y} &= \sum_{m=1}^{\infty} \sum_{p=1}^{2\pi/\Delta\theta} \mu_m^{\,2}\, c_{mp} \sin p\Delta\theta \cos(mt\,\Delta\mu + \phi_{mp}) \\
\ddot{z} &= -\sum_{m=1}^{\infty} \sum_{p=1}^{2\pi/\Delta\theta} \mu_m^{\,2}\, c_{mp} \sin(mt\,\Delta\mu + \phi_{mp})
\end{aligned}\right\} \tag{10}$$

We are interested in the spectrum of $|H(t)|^2 = \ddot{x}^2 + \ddot{y}^2$ and this can be obtained by following a procedure similar to that used by RICE (1945).

Equations (10) are first rewritten in the form

$$\ddot{x} = \tfrac{1}{2} \sum_{m=-\infty}^{\infty} \sum_{p=1}^{2\pi/\Delta\theta} \mu_m^{\,2}\, c_{mp} \cos p\Delta\theta\, e^{i(mt\Delta\mu + \phi_{mp})}$$

where it is taken that

$$c_{mp} = c_{(-m)p}$$

$$\phi_{mp} = -\phi_{(-m)p}$$

Then, after some reduction,

$$|H(t)|^2 = \tfrac{1}{4} \sum_{m=-\infty}^{\infty} \sum_{p=1}^{2\pi/\Delta\theta} \sum_{n=-\infty}^{\infty} \sum_{q=1}^{2\pi/\Delta\theta} \mu_m^{\,2}\, \mu_n^{\,2}\, c_{mp}\, c_{nq} \cos(p-q)\,\Delta\theta\, e^{i[(m+n)t\Delta\mu + \phi_{mp} + \phi_{nq}]}$$

Writing $m + n = k$ and adding conjugate terms gives

$$|H(t)|^2 =$$

$$\tfrac{1}{2} \sum_{k=0}^{\infty} \sum_{m=-\infty}^{\infty} \sum_{p=1}^{2\pi/\Delta\theta} \sum_{q=1}^{2\pi/\Delta\theta} \mu_m^{\,2}\, \mu_{k-m}^{\,2}\, c_{mp}\, c_{(k-m)q} \cos(p-q)\,\Delta\theta \cos\left[kt\,\Delta\mu + \phi_{mp} + \phi_{(k-m)q}\right] \tag{11}$$

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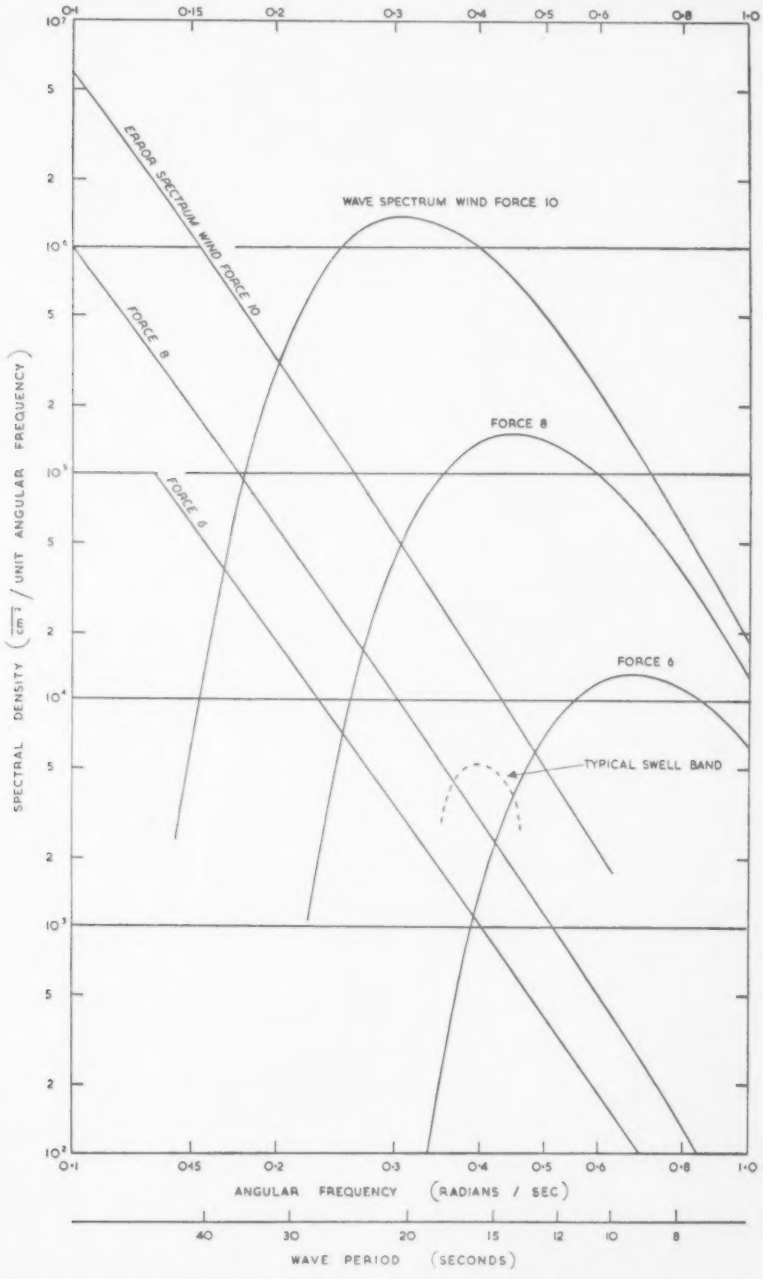

Fig. 1. Wave spectra computed from NEUMANN's formula for an equilibrium wave system, and the spectra of the errors introduced by measuring the waves using a buoy containing an unstabilised accelerometer whose output is integrated twice. Note that for wind force 10 the equilibrium is never reached in nature. The dotted line shows a typical band of swell on the West coast of Britain.

The power in the components with frequency $k\,\Delta\mu$ represents the power of $|H(t)|^2$ in a frequency interval $\Delta\mu$ centred about this frequency, and using equation (3) is therefore $4g^2\,W(k\,\Delta\mu)\,\Delta\mu$. The instantaneous amplitude of the sum of these components is the right-hand side of equation (11) with the first summation omitted. The power is the time mean of the square of the instantaneous amplitude. The expression becomes rather involved and will not be written down here, but the majority of terms contain the cosine of a random phase angle and are thus randomly positive and negative and on the average cancel one another. However, there are a number of terms which are consistently positive, and the power is therefore the sum of these. This gives

$4g^2\,W(k\Delta\mu)\,\Delta\mu =$

$$\tfrac{1}{4}\sum_{m=-\infty}^{\infty}\sum_{p=1}^{2\pi/\Delta\theta}\sum_{q=1}^{2\pi/\Delta\theta}\mu_m{}^4\,\mu_{k-m}{}^4\,c_{mp}{}^2\,c_{(k\ m)q}{}^2\cos^2\left[(p-q)\,\Delta\theta\right] \tag{12}$$

If the two-dimensional wave-height spectral density is $S(\mu,\theta)$ then

$$\tfrac{1}{2}\,c_{mp}{}^2 = S(\mu,\theta)\,\Delta\mu\,\Delta\theta$$

Taking limits as $\Delta\mu$ and $\Delta\theta$ tend to zero, and writing

$$k\Delta\mu = \sigma \qquad \text{and} \qquad p\Delta\theta = \theta \text{ and } q\Delta\theta = \psi$$

$$4g^2W(\sigma) = \int_{-\infty}^{\infty}\int_0^{2\pi}\int_0^{2\pi}\mu^4(\sigma-\mu)^4\,S(\mu,\theta)\,S(\sigma-\mu,\psi)\cos^2(\theta-\psi)\,d\mu\,d\theta\,d\psi \tag{13}$$

Expanding $S(\mu,\theta)$ into its angular harmonics, that is, writing

$$S(\mu,\theta) = \frac{1}{\pi}\left\{\tfrac{1}{2}\,\alpha_0(\mu) + \sum_{n=1}^{\infty}\left[\alpha_n(\mu)\cos n\theta + \beta_n(\mu)\sin n\theta\right]\right\} \tag{14}$$

equation (13) after some manipulation becomes

$4g^2\,W(\sigma) =$

$$\tfrac{1}{2}\int_{-\infty}^{\infty}\mu^4(\sigma-\mu)^4\left[\alpha_0(\mu)\,\alpha_0(\sigma-\mu) + \alpha_2(\mu)\,\alpha_2(\sigma-\mu) + \beta_2(\mu)\,\beta_2(\sigma-\mu)\right]d\mu \tag{15}$$

This equation can be greatly simplified if it is assumed that the angular distribution is the same at all frequencies. If P, Q and R are constants independent of μ it is then possible to write.

$$\alpha^2(\mu) = \mathrm{P}\,\alpha_0(\mu)$$

$$\beta_2(\mu) = Q\,\beta_0(\mu)$$

and

$$\alpha_2{}^2(\mu) + \beta_2{}^2(\mu) = (\mathrm{P}^2 + Q^2)\,\alpha_0{}^2(\mu) = R^2\,\alpha_0{}^2(\mu) \tag{16}$$

Giving

$$4g^2\,W(\sigma) = \tfrac{1}{2}(1+R^2)\int_{-\infty}^{\infty}\mu^4(\sigma-\mu)^4\,\alpha_0(\mu)\,\alpha_0(\sigma-\mu)\,d\mu \tag{17}$$

Now it will be seen from equation (14) that $\alpha_0(\mu)$ is the total wave energy at a frequency μ integrated over all directions, and it is therefore $S(\mu)$.
Using equation (6), the final result is thus

$$E(\sigma) = \frac{1}{8g^2\sigma^4}(1 + R^2)\int_{-\infty}^{\infty} \mu^4 (\sigma - \mu)^4 S(\mu) S(\sigma - \mu)\, d\mu \qquad (18)$$

From equation (16) R is the ratio of the amplitude of the second angular harmonic to the total energy, so that if the waves come from a narrow range of directions, $R = 1$ and equation (18) reduces to equation (7).

DISCUSSION OF THE RESULTS

There is at present very little information available about the angular distribution of wave energy, even in a locally generated sea, and it is not practicable to compute equation (17). However, the angular distribution has little effect on the shape of the error spectrum, and changes its magnitude by a ratio not exceeding 2 : 1. PIERSON (1957) has computed the even angular harmonics for a particular locally generated sea, and finds that the second harmonic has in this case an amplitude approximately 0·6 of the total energy for frequencies near those carrying most wave energy (note that R used here is 0·5 times PIERSON's C_1). He finds it varies considerably with frequency, but using the value of 0·6 would give a reduction in the error spectrum of 32 per cent compared with the unidirectional case. Thus, the results computed for a unidirectional spectrum may be regarded as an upper limit.

The computation interval $\Delta\mu$ used in computing the error spectra shown was 0·2 rad/sec for wind forces 6 ($v = 1{\cdot}2 \times 10^3$ cm/sec) and 8 ($v = 1{\cdot}8 \times 10^3$ cm/sec) and was 0·1 rad/sec for wind force 10 ($v = 2{\cdot}6 \times 10^3$ cm/sec). These intervals are rather large, but give sufficient accuracy in view of the other uncertainties. Apart from the directional uncertainty, the NEUMANN Spectrum itself is no more than an intelligent guess at the true wave spectrum. For example, the NEUMANN Spectrum for a force 10 wind shows appreciable spectral densities for wave periods in the region of 30 sec whereas in nature we have never detected ordinary wave components with periods of greater than 24 sec. NEUMANN explains this by the fact that for force 10 winds, fetches and durations sufficiently long to generate a fully arisen sea never occur, but one would expect some energy to go into waves of these periods with natural fetches and durations if the spectrum is correct for a fully arisen sea. Thus the results must be regarded as very approximate and cannot be used for correcting a measured wave spectrum.

Since no wave components with angular frequencies below 0·25 rad/sec (25 sec period) have ever been detected in nature, an electrical filter may be included in the system which removes all components with frequences below this. Assuming a perfect high-pass filter, the errors may be summarized as follows :

Wind force	6	8	10
Error in spectral density at frequency of greatest density	0·9%	1·3%	2·8%
Error in r.m.s. wave height with high-pass filter	3·9%	1·6%	1·1%

These errors are probably not serious for most purposes.

Typical swell from a distant North Atlantic storm could not in any case be measured in the presence of a local wind greater than about force 6, and the error signal under these conditions would probably not obscure it but would prevent accurate measure-

ment of its spectrum. Under similar conditions when a very long low swell from a storm in the Southern Oceans might be detectable in the absence of these errors, the error signal could obscure it completely. These critical conditions are, however, unusual and in general the errors seem unlikely to be important.

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Microbiology and the chief problems in the Black Sea

A. E. KRISS

(*Received* 14 *March* 1958)

Summary—Micro-organisms inhabit not only the oxygen zone but also the entire hydrogen-sulphide area of the Black Sea. Their average biomass per m^3 of water in the oxygen zone is lower than in the hydrogen sulphide region. In the latter are chiefly peculiar filamentous autotrophic forms utilizing hydrogen sulphide in their life processes. They are good indicators of the water exchange between the oxygen and hydrogen-sulphide zones of the Black Sea. At the bottom in the deep parts of the Black Sea the concentration of microbial organisms is similar to that in the mud of the Gulf of California. The use of the Black Sea, as suggested, for the disposal of the industrial radioactive wastes, if realized, would no doubt lead to dangerous consequences. Radioactive substances would be transferred in a comparatively short time via bacteria through the links of the food chains, to commercial fish.

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The Black Sea is a unique body of water. The surface layer down to depths of 125-225 metres is oxygenated and inhabited by plants and animals, but below this, where the water contains hydrogen sulphide, only micro-organisms occur. In places this lower layer is more than 2000 m in depth. The differences between the two zones, it was thought in the 1920's, indicated that the exchange between them was very limited and due chiefly to diffusion and to the sinking of more saline water from the Bosporus displacing a like amount of the deep water. In the late thirties and early forties, it appeared on theoretical grounds that the water is mixed to a depth of 1000 m by the circular currents resulting from the effects of the wind and the Coriolis force.

Biological productivity is closely related to the exchange between these two zones. In the upper biotic layer, the nutrients are continually being removed through the sinking of dead plants and animals into the deeper water, without, it was thought earlier, any mechanism for returning them to the upper layer. Although the earlier work indicated a low productivity in the biotic layer to support this concept, later results in the deeper offshore parts of the Black Sea do not agree.

Recently a committee of the United Nations Organization recommended the bottom of the Black Sea as a possible disposal ground for radioactive industrial wastes, on the supposition that conditions prevail there to isolate them for a sufficiently long period to insure their decay. This was based on the assumption that the productive oxygenated zone is isolated from the hydrogen sulphide zone where biological processes and consequently the transformation of organic and inorganic compounds are suppressed.

Through the cycling of chemicals, micro-organisms play an important role in biological productivity and they may also be indicative of hydrological phenomena. Thus, extensive work on the microbiology of the deep offshore waters of the Black Sea has in recent years contributed toward an understanding of the problems outlined above.

(1)

The microbiological data contradict the concept of an extremely weak exchange between the hydrogen sulphide and oxygenated zones due to density differences. Mathematical calculations (VODYANITSKY, 1948) indicate that a constant sinking in the surface layers in the open Black Sea, where there are circular currents, and an ascent of the deeper waters in the central parts, effect a water exchange down to considerable depths, an exchange amounting to approximately six times the volume of the river water entering the Black Sea.

Microscopic observation proves that in addition to the vertical circulation of a thermal character, which in winter causes the ascent of water from the hydrogen sulphide zone, there are other factors which aid in mixing the waters in the depths of the Black Sea. Indicators of these processes are the peculiar filamentous micro-organisms (Fig. 1), endemic in the hydrogen sulphide zone, where there may be thousands of them per millilitre of water. These occur only accidentally and in relatively small numbers in the oxygenated zone, only when the waters are sufficiently mixed.

Samples of micro-organisms at various levels from the surface down to 200 m taken in June and February at a station in the Black Sea thirty miles off the coast bear this out. Thus, as a result of the vertical circulation caused by the winter surface cooling, there is a twelve-fold increase in the microbial biomass in winter at depths of 125-150 m within the oxygenated zone. This turns out to consist of filamentous forms endemic in the hydrogen sulphide zone. These peculiar Black Sea bacteria, not readily confused with ordinary microbial forms, are evidence of the ascent of water from the hydrogen sulphide to the oxygenated zone. They afford a measure of the quantity of water exchanged. Such a water exchange not only occurs during the period when the winter circulation is strongest, but also is due to other factors that cause active mixing. Along the north-west coast of the Black Sea off Odessa, for example, large quantities of filamentous bacteria were found following strong north winds (LEBEDEVA, 1953) due to upwelling in the offshore waters.

At present, plans are being made for seasonal, and later for monthly, observations of changes in the abundance of filamentous micro-organisms in the upper layers of the hydrogen sulphide and in the lower layers of the oxygenated zones. Comparison of the data should permit us to determine the extent of the water mass affected by the vertical circulation and consequently the intensity of the water exchange between the hydrogen sulphide and oxygenated zones under various hydrometeorological conditions.

(2)

VODYANITSKY (1948) rightly pointed out that the water exchange between the oxygen and the hydrogen sulphide zones extends into deep water, as shown by the vertical distribution of the hydrogen sulphide. Thus, its concentration gradually increases down to 1000 m, but it does not fluctuate significantly at greater depths. Although in the Black Sea, sulphate-reducing and putrefactive bacteria are scattered throughout the water mass, the largest amounts of hydrogen sulphide are produced on the bottom (KRISS and RUKINA, 1949). The decrease in hydrogen sulphide content between 1000 m and the upper boundary of the hydrogen sulphide zone is caused by the downward transport of oxygen from the oxygenated layer above. Similarly,

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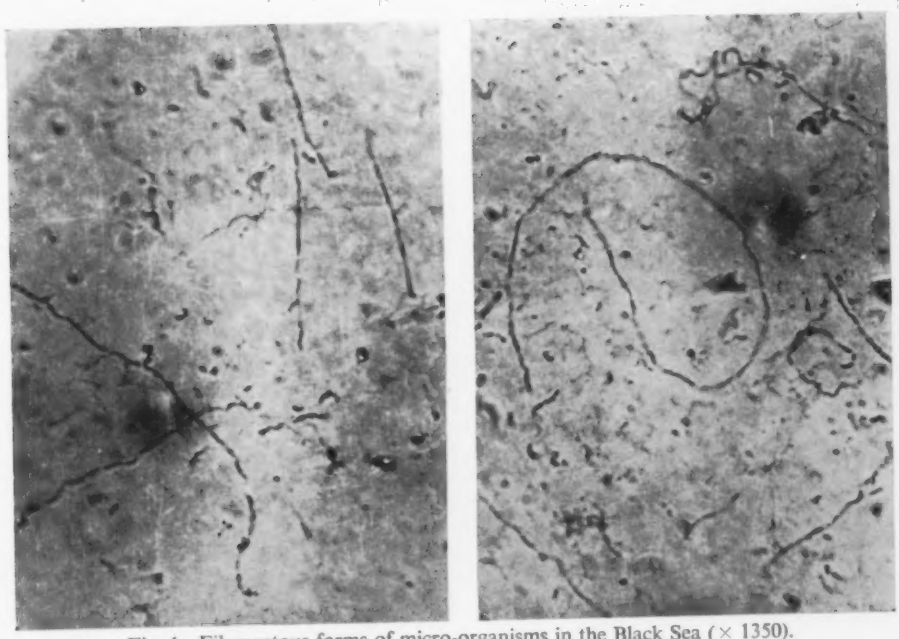

Fig. 1. Filamentous forms of micro-organisms in the Black Sea (× 1350).

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Table 1. Average number and biomass of micro-organisms at different sea and ocean depths

Layers of water (m)	Southern part of the Caspian Sea			Middle part of the Caspian Sea			The Black Sea*		The Pacific Ocean			The North Pole†	
	Number of stations	Number of Bacteria in thousand per 1 ml	Biomass (mg/m³)	Number of stations	Number of Bacteria, in thousand per 1 ml	Biomass (mg/m³)	Number of Bacteria, in thousand per 1 ml	Biomass (mg/m³)	Number of stations	Number of Bacteria, in thousand per 1 ml	Biomass (mg/m³)	Number of Bacteria, in thousand per 1 ml	Biomass (mg/m³)
0–50	9	224	44·8	7	136	27·2	167	33·6	9	125	25	9	1·8
50–100	6	52	10·4	5	39	7·7	38	7·7	9	53	10·5	6	1·2
100–200	3	19	3·8	4	17	3·4	54	19·7	9	26	5·1	3	0·6
200–500				3	5·5	1·1	69	32·0	9	6	1·1	0·6	0·1
500–750				1	1	0·2	65	38·6	9	1·2	0·24	0·2	0·05
750–1000							61	41·0	9	2	0·45	0·5	0·1
1000–1500							56	42·2	9	1·9	0·4	0·6	0·12
1500–2000							58	43·1	9	1·4	0·3	0·4	0·08
2000–3000									10	0·4	0·08	0·15	0·03
3000–4000									9	0·3	0·05		
4000–5000									5	0·2	0·03		
5000–6000									2	0·04	0·009		
6000–7000									2	0·06	0·01		
7000–8000									1	0·08	0·02		
8000–9000									1	0·04	0·008		

*Average of five stations.
†Average of two stations

the deep water transports the nutrient substances and micro-organisms abundant in the depths of the Black Sea upward into the biotic layer. These nutrient materials are necessary in plant and bacterial development of the open sea far from river mouths.

An increase in the numbers of micro-organisms, which utilize the organic products of metabolism and decay, accompany an increase in plant and animal populations. In the layer of active photosynthesis in the Black Sea, the average biomass of micro-organisms (33 mg per m^3 of water in the upper 50 m) is comparable to that found in the Caspian Sea (Table 1). Thus, the organic substances apparently available for micro-organisms are similar. This suggests a similarity in the productivity in the photosynthetic zone in the offshore regions of the Black and Caspian Seas. In the Pacific Ocean, on the other hand, in the vicinity of the Kurile Islands, the microbial biomass in the upper layers is lower (Table 1).

In the Black Sea, below fifty metres, there is a decrease in the microbial biomass (7·7 mg per m^3 of water). This decrease to a small fraction (i.e. 1/10 to 1/1000) as compared with the upper layers, at depths of 50-75-100 m to the bottom is usual in the Caspian Sea (KRISS, 1956), in the Pacific Ocean near the Kurile Islands (KRISS and BIRYUZOVA, 1955), and in the vicinity of the North Pole (KRISS, 1956). In the Black Sea, however, at the upper boundary of the hydrogen sulphide zone (i.e. at 125-150-200 m), the microbial biomass increases again and then fluctuates only slightly from 200-300 m down to the bottom at 1750-2000 m (Table 1). It is significant that the average bacterial biomass in the hydrogen sulphide zone (200-2000 m) averages 1·5 to 2 times that in the oxygenated zone (0-200 m) (Table 1). Hence, in addition to the presence of hydrogen sulphide in the Black Sea, the second peculiarity is the great abundance of micro-organisms in the depths of the hydrogen sulphide zone.

Table 2. Comparative quantitative characteristics of a biomass of micro-organisms, phytoplankton and zooplankton in the Black Sea

	Average biomass 1 m^3, (mg)	*Average biomass under 1 m^2 of sea surface, (g)*	*Total biomass of the Black Sea, in million tons‡*
Micro-organisms (oxygen zone) 0-200 m	20	74	1·3
Micro-organisms (hydrogen sulphide zone) 200-2000 m	40		18·5
Phytoplankton* 0-200 m	59	11·6	4·0
Zooplankton† 0-200 m	184	36·8	12·4

*Date obtained by MOROZOVA-VODYANITSKAYA (1950).
†Data obtained by KUSMORSKAYA (1950).
‡According to SHOCKALSKY, SNEZHINSKY and CHIZHICKOV (ZENKEVITCH, 1947), water volume is 67594 km^3 in the oxygen zone and 462360 km^3 in the hydrogen sulphide zone.

The large microbial biomass in the hydrogen sulphide regions of the Black Sea consists chiefly of filamentous bacteria of the purple sulphur variety (KRISS and RUKINA, 1953). It is known that hydrogen sulphide serves as a hydrogen donor for purple-sulphur bacteria in the assimilation of carbon dioxide, a photosynthetic process requiring energy from the sun. However, in the great depths of the Black

Sea where light does not penetrate, there must be other energy sources for sulphur bacteria to use in assimilating carbon dioxide. Possible energy sources are organic compounds in the water and radioactive disintegration. It seems doubtful that organic substances in the hydrogen sulphide zone are an important source, because they are at great depths in the form of humus which is assimilated with great difficulty by micro-organisms. Autotrophic development of micro-organisms from radioactive disintegration (or radiosynthesis) might be similar to photosynthesis or chemosynthesis and could explain the accumulation of the huge microbial mass in the hydrogen sulphide regions of the Black Sea. Since most of the Black Sea basin is 1500 to 2000 m in depth (ARCHANGELSKY and STRACHOV, 1938), the biomass of micro-organisms under each square metre of sea surface is more than 1·5 times the phytoplankton and zooplankton biomass (Table 2). Indeed, the microbial biomass is even greater than that of the plankton and nekton together.

New organic substances formed in the hydrogen sulphide zone by autotrophic micro-organisms are utilized in a number of processes, particularly in the food chain in the oxygen zone. Thus, in winter when the vertical circulation is greater, the microbial biomass may increase to as much as 53 mg/m³ in the lower layers of the oxygenated zone through a transport of the filamentous bacteria-autotrophs upwards from the hydrogen sulphide zone (LEBEDEVA, 1953). This exceeds the biomass of the copepod, *Calanus*, which also spends a considerable portion of the day in the deeper part of the oxygenated zone. As LEBEDEVA found filamentous bacteria in the guts of these copepods, *Calanus* very possibly feeds on them. Further research has been planned to determine the significance of the micro-organisms from the hydrogen sulphide zone of the Black Sea as a source of food for the zooplankton, as a step in the food chain supporting the commercial fisheries.

Table 3. *Quantitative content of micro-organisms in the surface layers of muds at the maximum depths of the hydrogen sulphide regions of the Black Sea* (*in* 1 *g of wet mud*)

Year	*Number of stations*	*Sea depth in m*	*Total number of microbes by direct count in millions*	*Number of colonies in fish pepton agar in thousands*	*Titer of micro-organisms*					
					Protein decomposing		*Sulfate-reducing*	*Denitrifying*	*Thiobacteria*	*Nitrifying*
					Aerobes	*Anaerobes*				
1946	2	2164		159	10^6	10^2	10^4	10^7	10^4	
	3	2150		513	10^6	10^5	10^5	10^7	10^5	
	4	2100		310	10^6	10^5	10^6	10^7	10^5	
	5	1730		224	10^6	10^6	10^6	10^5	10^5	
1948	4	2160		10	10^6	10^3	10^3	10^5	10^6	10^3
	7	2140		50	10^6	10^4	10^1	10^7	10^7	10^3
	8	2120		320	10^7	10^3	10^1	10^7	10^7	10^3
	11	1680		60	10^4	10^2	10^4	10^5	10^6	10^3
1949	1	2130	2962	10·8						
	2	2170	2499	30						
	3	2217	1522	50						

(3)

Until recently, it was believed that the only inhabitants of the bottom mud of the Black Sea were those micro-organisms that reduce sulphate to hydrogen sulphide.

Only within the last decade or so has it been shown that the upper layers of the mud deposits in the deeper parts of the Black Sea are densely populated with micro-organisms which utilize a variety of organic and inorganic compounds.

The micro-organisms in one gram of mud taken from various samples from the deepest parts of the Black Sea floor developed 10^5 colonies of bacteria (Table 3). In media for ammonifying, denitrifying, sulphate-reducing and sulphate-oxidizing microbes 10^6 to 10^7 developed per gram of mud. To grasp the significance of these figures, one must point out that in the top layers of mud from the deep waters of the Sea of Okhotsk, the number of these same groups of micro-organisms usually amount only to a fraction (1/1000 to 1/10,000) as much (KRISS and RUKINA, 1952). The concentration of microbial life on the bottom of the Black Sea is nearly equal to that reported by ZOBELL (1946) in the bottom sediments off the California coast. This is indicative of the similarity in the intensity of the microbial action in the two localities.

The high content of hydrogen sulphide in the bottom layers of the Black Sea does not visibly inhibit the capacity of micro-organisms to use organic matter and other materials in their life processes. They participate in the overturn of carbon, nitrogen, sulphur and phosphorus (KRISS, *et al.* 1951), as shown experimentally and also by the

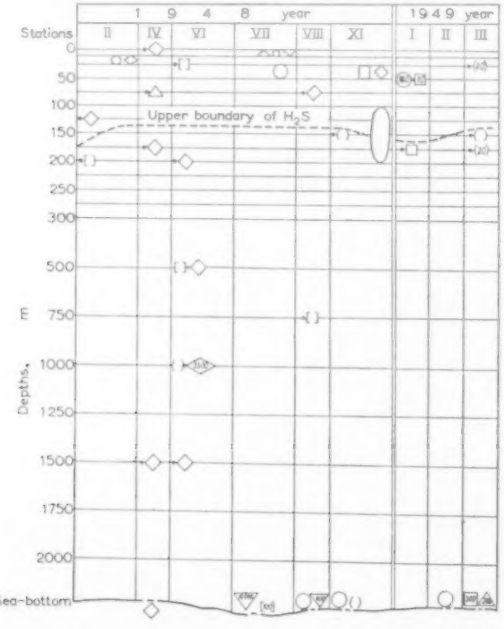

Fig. 2. Distribution of some species of non-sporeforming bacteria in the Black Sea.
Symbols used :
○—*Bact. album, strain E* ; □—*Bact. album, strain F* ; △—*Bact. album, strain G* ; ( )—*Bact. album, strain J* ; ▽—*Bact. album, strain K* ; [ ]—*Chromobacterium chlorinum, strain A* ; ◇—*Chr. aquatile, strain B.*

increased concentration in the great depths of ammonia, nitrogen, methane, hydrogen, carbonates, free carbon dioxide and phosphates (DANILCHENKO and CHIGIRIN, 1926 ; CHIGIRIN and DANILCHENKO, 1930). The accumulated reduced materials resulting from microbial processes on the bottom of the Black Sea are used by other micro-

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organisms as an energy source just as are the organic compounds (KRISS and RUKINA, 1949). It is clear that with the great mass of various micro-organisms in the mud of the Black Sea, the bottom represents a gigantic biochemical laboratory that determines the unique hydrochemical regime of that basin.

Dumping radioactive industrial wastes into the depths of the Black Sea may have dangerous consequences, since these radioactive substances would thus be drawn into various microbial processes. Micro-organisms are the forms of life most resistant to radioactivity. Hence, it can be expected that radioactive materials will be transported into the oxygenated zone by the microbial cells, by passive water exchange or by their own vital movement.

Among the various bacteria of the Black Sea, there are some that are widely circulated in the waters and at the bottom (KRISS, *et al.* 1950 ; KRISS, *et al.* 1954). Some species of asporogenic bacteria are found in the Black Sea at various depths both in the oxygenated and hydrogen sulphide zones, and on the bottom in great quantities (Fig. 2). Clearly, the transfer of bacteria contaminated by radioactive wastes from the depths of the Black Sea into the upper layers where plants and animals enter into the food chain culminating in the commercial fisheries would also contaminate these links in the food chain. From available data, it appears that this could occur within a relatively short period.

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Bathyscaph measurements of daylight penetration into the Mediterranean

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(*Received* 18 *July* 1958)

Abstract—The penetration of blue daylight down to 300 m was measured during dives with the bathyscaph *Trieste* south of Capri. The results show the gradual increase in daylight extinction from the surface to 100 m which is typical for clear water. The transparency in the deep layers is much lower than that in clear water ; it is suggested that the additional extinction is due to particles.

INTRODUCTION

A GENERAL survey of the scope offered by the bathyscaph for oceanographic research has been given by PICCARD and DIETZ (1957). Among the special advantages of the bathyscaph they mention is that when using electronic devices the need for long electric cables is eliminated.

In particular, the study of daylight penetration into the sea by means of the bathyscaph makes possible a high degree of accuracy in the measurements. The necessary depth recording is obtained exactly by a depth gauge in the cabin. In addition, the high stability of the bathyscaph eliminates the fluctuations in daylight observations which, with a conventional photometer suspended from a cable, are caused by the drift and roll of the ship.

The present work comprises some measurements in underwater illumination which were carried out during dives with the bathyscaph *Trieste* south of Capri in the summer of 1957. The primary object of the experiments was to study daylight extinction and its variation down to depths of 300 m.

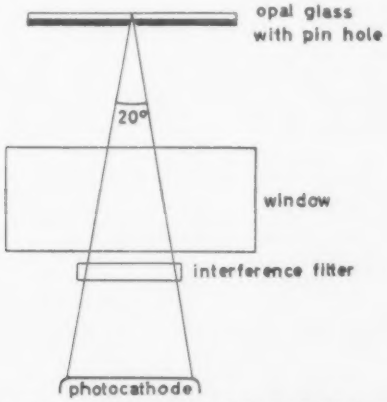

Fig. 1. Optical arrangement of the bathyphotometer.

BATHYPHOTOMETER

The submerged unit of the photometer employs a photomultiplier tube. The case of this unit has previously been used as a deep-sea camera by JERLOV and KOCZY

(1951). It was mounted on the top of the bathyscaph freely exposed to daylight. The phototube was connected by a shielded conductor cable with the electrical units installed in the cabin.

The optical arrangement of the photometer is a pinhole system by which a cone of light from the opal glass reaches the tube (Fig. 1). The apex angle of the cone is 20° which ensures that a narrow spectral range (width 12 mμ) is transmitted through the interference filter. The peak of the transmitted radiation is at 481 mμ close to the wave-length which is most penetrating in clear ocean water (JERLOV, 1951). Below 200 m in the ocean the light is sufficiently monochromatic that the colour filter is not needed. Hence the full sensitivity of the photometer provided only with an opal glass can be utilized.

Without entering into a general discussion of photomultiplier tubes, a brief description of the electrical units will be given. The power supply in the cabin was a 500 v battery pack connected with a rotary converter which produced 220 v a.c. for the high voltage unit. Voltage fluctuations at the input to this unit were manually controlled. The high voltage unit employed a selection of 9 steps of high voltage accurately reproducible from 320 to 1200 v.

A Du Mont Type 6291 10-stage multiplier phototube of the end-window type with an average sensitivity of 60 μa/lumen, was used. The phototube was shielded from the geomagnetic field by a mu-metal shield as suggested by WERTHEIM (1954, unpublished).

The measuring microammeter has a full-scale sensitivity of 100 μa which can be reduced to ½ and ⅓ by means of precision load resistors. In addition, a smoothing circuit can be employed which introduces the time constants of 1, 5 and 10 sec. respectively in order to reduce the light fluctuations in the uppermost layers caused by waves and swell. The zero of the microammeter was adjustable.

The calibration unit is the same as used for the deep-sea camera (JERLOV and KOCZY, 1951). The photometer provided with the interference filter was calibrated in terms of irradiance in $\mu W/cm^2$ by regulating the lamp current and by introducing neutral density filters.

One of the gauges available for depth determinations in the cabin has a full scale of 300 m and can be read to within ± 1 m. The second gauge to be used below 250 m has a smaller accuracy of ± 10 m. Appropriate corrections were made for the difference in depth between the gauges and the submerged unit of the photometer.

OBSERVATIONS

The first two descents with the *Trieste* for the season were made to 300 m about 5 miles south of Capri on 1 July 1957. Next day a dive was made to 600 m, at which depth should be near the limit for visual perception of light according to earlier observations. Unfortunately the original plans to extend the measurements to deeper water became impractical : consequently the above three dives provided the present data.

The results of measurements are combined into one series which is presented in Table 1 and Fig. 2. The shape of the logarithmic curve in Fig. 2 exhibits the bending typical for clear water (JERLOV, 1951). The gradual increase in extinction from the surface to 100 m is more marked than previously found at other localities. This is illustrated by a comparison with two *Albatross* stations in the Mediterranean, St. 277

Table 1

Depth *m*	*Percentage of surface radiation* *Blue light*		
	Albatross		*Trieste*
	St. 294	*St.* 277	*south of Capri*
0	100	100	100
10	71	82	85
25	50	62	63
50	21	29	31
75	7·2	11	13
100	1·8	3·8	3·5
150	0·18	0·46	0·26
200	0·021	0·078	0·021
250			0·0020
300			0·00024

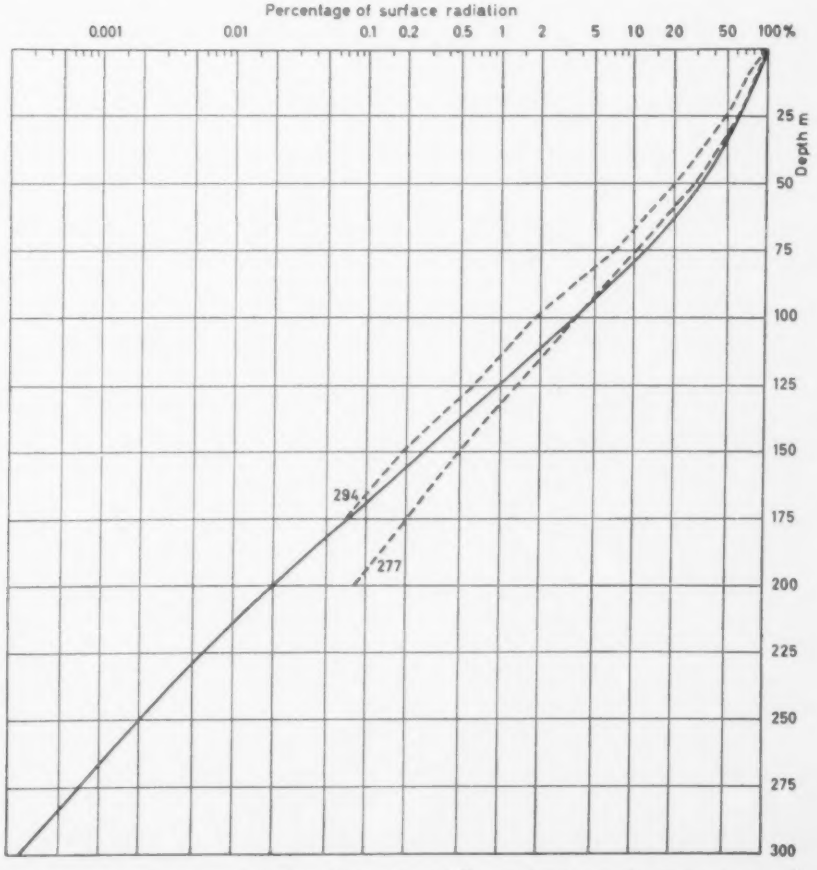

Fig. 2. Percentage of surface radiation (481 mμ) at different depths south of Capri according to observations from the bathyscaph *Trieste* on 1 and 2 July, 1957. Dashed lines indicate logarithmic curves for *Albatross* station 277, south-east of Crete, and 294 in off-shore waters in the Tyrrhenian Sea.

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south-east of Crete and St. 294 in off-shore waters in the Tyrrhenian Sea (Table 1). The daylight penetration to 100 m south of Capri is nearly the same as that at St. 277 whereas light is more rapidly extinguished in deeper strata. It can be visually observed that the surface stratum south of Capri possesses a remarkable transparency, which is also manifest in the brilliant blue colour. This high clarity is thus similar to that in the eastern Mediterranean and it approaches that in the Sargasso Sea, which is the clearest ocean water.

Such a high transparency appears only when dissolved, light-absorbing matter in the water, particularly yellow substance, is almost absent. Actually the water off Capri is only slightly contaminated by fresh-water discharge. But the clear water is also an effect of a low content of particulate matter coupled with a fairly poor plankton population.

On the other hand, the transparency in the deep layers south of Capri is much lower than that in clear ocean water. The deep measurements available for comparison are the observations by JERLOV (1951), JERLOV and KOCZY (1957) and CLARKE and WERTHEIM (1956) which give closely agreeing extinction-coefficients between 0·033 and 0·039. From the *Trieste* data for the depth interval 100-300 m an extinction-coefficient of 0·048 is obtained which is somewhat higher than that displayed by St. 294, occupied not far from Capri. Considering that the present dives were made not far from land it is suggested that the additional extinction is due to particles which are usually abundant near the submarine slopes.

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The zoogeographical distribution of the deep-water bottom fauna in the abyssal zone of the ocean

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(*Received* 14 *April* 1958)

Abstract—Analysis of the geographical distribution of certain groups of benthic invertebrates (1031 species) in depths greater than 2000 m showed that 84 per cent of the species are confined to a single ocean and only 4 per cent occur in the Pacific, Atlantic and Indian Oceans. Each ocean has its own characteristic fauna. In the Pacific and Atlantic Oceans, 75 per cent of the deep-sea species are endemic. In the Indian Ocean, the percentage is somewhat lower. However, the genera and families of deep-sea animals are generally widely distributed. The specificity (endemism) of the fauna increases with increasing depth of habitat.

Three zoogeographical regions can be distinguished in the abyssal zone of the ocean : the Pacific-North Indian, the Atlantic and the Antarctic. These may be divided into sub-regions and provinces. One of the chief factors affecting the distribution of deep-sea bottom fauna seems to be the configuration of the ocean floor, especially the macrorelief. Consequently, the boundaries between zoogeographical regions follow underwater ridges and other elevations.

The species of deep-sea bottom invertebrates with a wide vertical range generally have an extensive horizontal range as well. Almost all cosmopolitan deep-sea forms are eurybathic. The stenobathic species, on the contrary, occur only in a restricted area.

THE literature on investigations of the ocean depths by both Russian and foreign expeditions since the middle of the last century, as well as analyses of the deep-water fauna collected by the "*Vitjaz*" in the Far Eastern seas of the Soviet Union and the north-west part of the Pacific Ocean, make it possible to obtain some information on the distribution of 1031 species of deep-water Porifera, Coelenterata, Cirripedia, Isopoda, Decapoda, Pantopoda, Echinodermata (with the exception of Ophiuroidea), and Pogonophora, found at depths of over 2000 m. Of these species, 84 per cent are confined to one ocean, about 15 per cent occur in two oceans and only 4 per cent in all three. The genera and families on the other hand are, for the most part common to all three oceans.

Of the species common to more than one ocean, small numbers (2·1 per cent) are common to the Atlantic and Indian oceans and twice as many to the Indian and Pacific oceans. These figures contradict MADSEN's (1953) theory that the deep-water fauna of the Indian and Atlantic oceans are the more closely related.

In the Pacific and Atlantic oceans, 73·2 per cent and 76 per cent of the deep-water species respectively are endemic. The large percentage of deep-water species found only in the Atlantic indicates that the fauna there is no less distinctive than that in the Pacific. The Indian Ocean, on the other hand, has the smallest proportion of endemic deep-water species.

Another feature peculiar to the Indian Ocean fauna is that it is not uniform throughout the ocean. Only 2·4 per cent of the deep-water species are found both in the northern (north of the line between the Cape of Good Hope and Cape Naturalist) and southern parts. A very large number of species in the Indian Ocean also occur

in the Pacific Ocean (47·7 per cent and particularly in its northern part). In the southern Indian Ocean, there is an increasing number of deep-water species typical of the Atlantic, but most of them are Antarctic species found in the other oceans, but only south of 40°S. The distribution of the deep-sea fauna of the Indian Ocean agrees well with the paleogeographic reconstruction of the seas of the late Mesozoic especially with the contours of the Tethys. Accordingly, it reflects the influence of past geologic eras.

Table 1. *The number of deep-water species common to the different oceans with relation to the depth at which they occur*

Depths at which species occur	*Species common to Antarctic and all other oceans in percentage of Antarctic species (in round numbers)*			*Species common to West and East Atlantic in percentage of total No. of species in given area*	*Species common to western and eastern parts of the North Pacific in percentage of total No. of species in given area*
	Atlantic	*Indian*	*Pacific*		
Deep-sea species rising to depths of less than 2000 m	70	60	27	49	49
Species from depths below 2000 m	15	40	4·3	12·9	12·6
Species from depths below 3000 m	6	10	2·5	7·2	15·6
Species from depths below 4000 m	0	0	0	0	1·2

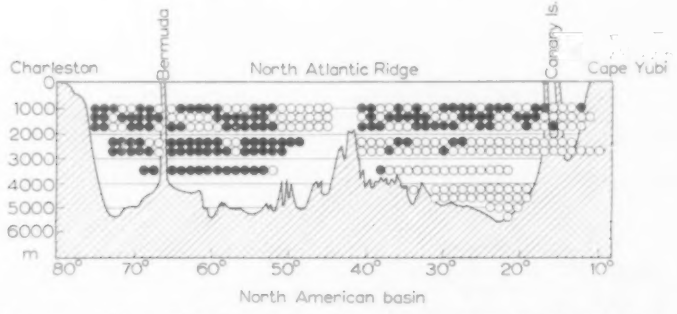

Fig. 2. Vertical cross-section of the North Atlantic Ocean to show the distribution of species of bottom invertebrates of the North American and North African basins, at various depths. The black circles represent the species of the North American basin, the open circles the species of the North African basin.

From the geographical distribution of the abyssal fauna and bottom invertebrates, we have divided the ocean into the following zoogeographical areas (Fig. 1). This division of the Abyssal Zone refers chiefly to the upper-abyssal sub-zone (3000-4500m). The boundaries separating the faunas at greater depths might be drawn rather differently due to the greater degree of isolation of the organisms living there. Thus, with increasing depth the faunas of the various areas become increasingly restricted (Table 1) or, in other words, the area of occurrence of the deep-water species tends

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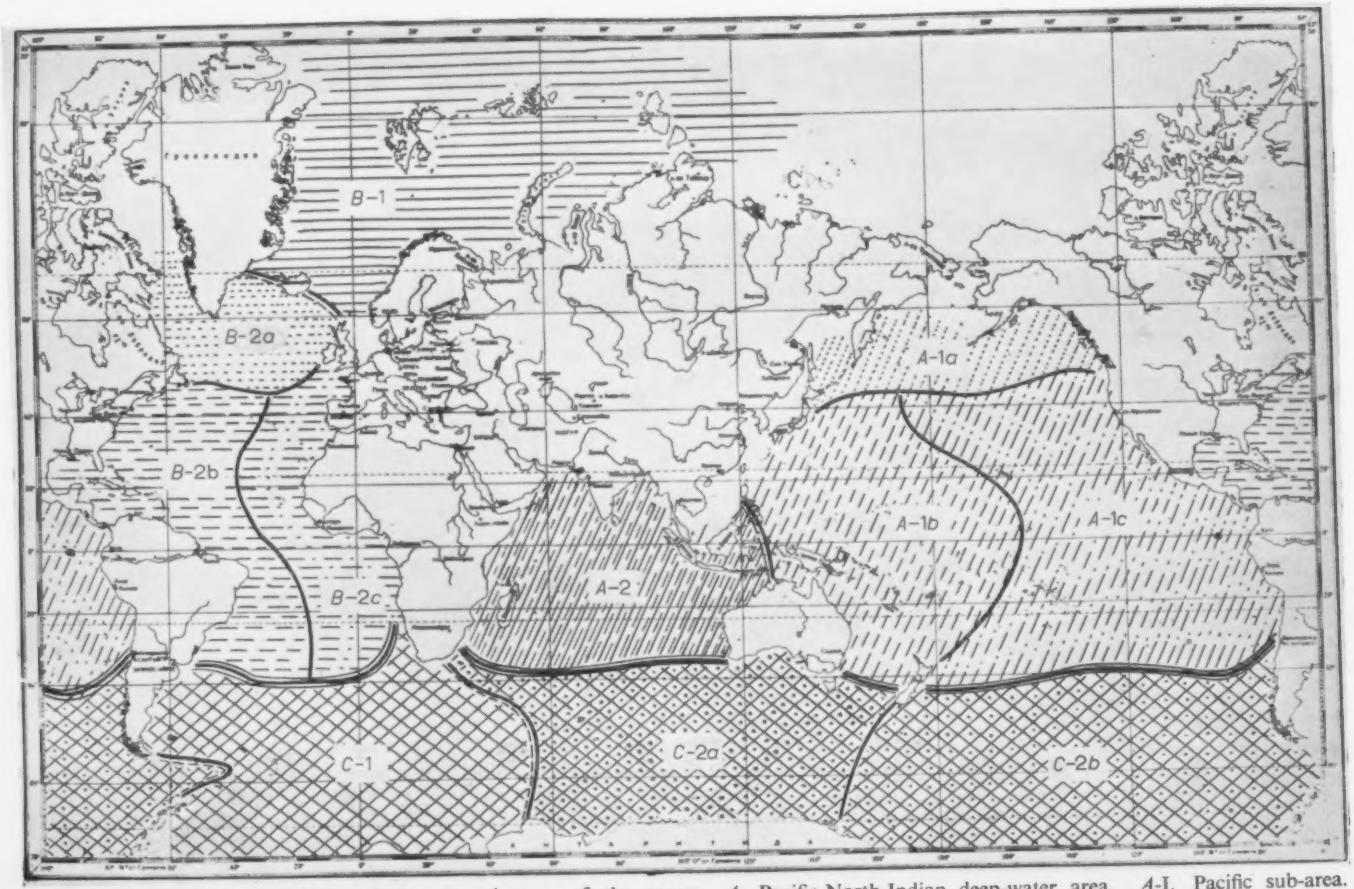

Fig. 1. Zoogeographical divisions of the abyssal zone of the ocean. *A*. Pacific-North-Indian deep-water area. *A*-I. Pacific sub-area. *A*-Ia. North Pacific Province. *A*-Ib. West Pacific Province. *A*-Ic. East Pacific Province. *A*-2. North Indian sub-area. *B*. Atlantic deep-water area. *B*-I. Arctic sub-area. *B*-2. Atlantic sub-area. *B*-2a. North Atlantic Province. *B*-2b. West Atlantic Province. *B*-2c. East Atlantic Province. *C*. Antarctic deep-water area. *C*-1. Antarctic-Atlantic sub-area. *C*-2. Antarctic-Indian-Pacific sub-area. *C*-2a. Indian Province. *C*-2b. Pacific Province.

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to decrease with depth. This agrees with the hypothesis for the endemism of the fauna in the ocean trenches at depths greater than 6000 m (ZENKEVICH, *et al.*, 1955 ; BRUUN, 1956).

The distribution of deep-water species is apparently restricted to certain areas by the relief of the bottom, especially by the features of the macrorelief (Fig. 2). Hence, the boundaries of the zoogeographical areas for the deep-water bottom fauna correspond with submarine mountain chains and elevations. The great majority of cosmopolitan deep-water species, which have a comparatively wide vertical depth range are eurybathic. In contrast, stenobathic species, with a limited vertical distribution, occur only in restricted areas. About 30 per cent species of the groups investigated were eurybathic and about 70 per cent stenobathic species (Fig. 3).

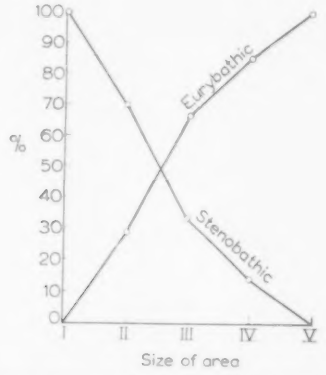

Fig. 3. Graph showing the relation between the extent of the areal distribution and the eurybathic characteristics of the species. The Roman numerals are arbitrary divisions to indicate the extent of these ranges.

I. Range limited to a very restricted portion of an ocean.
II. Range extends over half an ocean.
III. Range confined within the bounds of one ocean.
IV. Range extends throughout two oceans.
V. Range extends throughout all three oceans – or species with a pan-oceanic distribution.

Undoubtedly, there are other factors which also influence the distribution of the deep-water fauna – such abiotic factors as temperature, the nature of the bottom and pressure, and such biotic factors as the presence or absence of pelagic larvae, feeding habits, the distribution of food, etc.

In conclusion, although our knowledge of the causes of the geographical distribution of the deep-water bottom fauna is far from complete, we have a fairly clear idea of the general characteristics of the zoogeographical divisions of the upper abyssal zone of approximately 2000-4500 m, depths for which the greatest amount of data exist.

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Note : In studying the deep-sea fauna in depths greater than 2000 metres, the author has used data collected on Soviet and foreign expeditions culled from a search through complete series of numerous periodicals and expedition reports. More than 622 entries have been made in a card index and hence are too numerous to list here. For the tracks of the major expeditions exploring the oceans, see : G. SCHOTT, " Geographie des Indischen und Stillen Ozeans " (1935) and " Geographie des Atlantischen Ozeans " (1942), published by C. Boysen, Hamburg. Morskoi atlas Vol II, 1953. Isdanie Glavnogo Staba Voenno-Morskikh sil U.S.S.R.

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Flow estimate for the perpetual salt fountain

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(*Received* 25 *July* 1958)

STOMMEL *et al.* (1955) pointed out the " perpetual salt fountain " as an interesting oceanographical curiosity that might possibly be used for pumping up nutrient-rich deep water to the surface for ocean farming applications. The fountain would work in a region where there is a salinity minimum below the warm surface layer of the ocean. STOMMEL *et al.* state, " If a long tube were lowered from the surface to depth of low salinity water, and the deep water were slowly pumped to the surface through the tube, and the pump then disconnected, the water would continue to flow, by itself, forever. This remarkable phenomenon occurs because slow motion through the tube allows the water inside to attain the same temperature as the surrounding water. Its salinity, and hence density, is therefore less than that of its surroundings outside the tube, and hence the entire column of water inside the tube is buoyant with respect to the fluid outside at the same level. If the direction of pumping is reversed, so that the fluid initially goes downward, it will of course continue to flow downward forever on account of its excess in density over that of the water outside the tube."

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In order to estimate the rate of flow in the salt fountain, let us assume that a straight tube of length L extends slanting from the surface to a depth h in a horizontally stratified ocean. The vertical co-ordinate y is taken positive downward and zero at the surface, and $\theta(y)$ and $S(y)$ represent the temperature and salinity, respectively, of the ocean. Inside the tube the salinity is uniformly equal to $S(h)$ for upward flow and the temperature is designated by $\phi(y)$, steady state being assumed. Taking the temperature inside the tube as a function only of y presupposes complete mixing in any horizontal layer and leads to a slight over-estimate of heat conduction and hence flow rate especially in the case of laminar flow, but this will not seriously affect the results. The water density inside and outside the tube is taken as a linear function of temperature and salinity,

$$\rho = \rho_0 + \theta \frac{\partial \rho}{\partial \theta} + S \frac{\partial \rho}{\partial S} \tag{1}$$

compressibility effects being neglected. The coefficients $\frac{\partial \rho}{\partial \theta}$ and $\frac{\partial \rho}{\partial S}$ are taken as constants.

The temperatures inside and outside the tube are related by the equation

$$\frac{D\phi}{Dt} \equiv -\frac{vh}{L}\frac{d\phi}{dy} = \frac{2n}{w\rho cr}(\theta - \phi), \qquad \phi(h) = \theta(h) \tag{2}$$

where v is average velocity of flow through tube toward the sea surface, n is heat conductivity of tube material, c is specific heat of the sea-water, w is the wall thickness

and r the inside radius of the tube. Here r is assumed very large compared to w. D/Dt designates the material derivative following the mean motion of the water. Equation (2) has the solution

$$\phi(y) = \gamma e^{\gamma y} \int_y^h \theta(y')\, e^{-\gamma y'}\, dy' + \theta(h)\, e^{-\gamma(h-y)} \tag{3}$$

where

$$\gamma = 4\,nL/w\rho cvRh, \qquad R = 2\,vr/\nu$$

ν being the (constant) kinematic viscosity of the sea-water.

If we assume that the water is removed from the top of the tube as fast as it flows up, so that no additional head is formed, the excess of pressure at the bottom end of the tube over the hydrostatic head of water inside the tube is

$$\Delta p = g \int_0^h \left\{ [S(y) - S(h)] \frac{\partial \rho}{\partial S} + [\theta(y) - \phi(y)] \frac{\partial \rho}{\partial \theta} \right\} dy \tag{4}$$

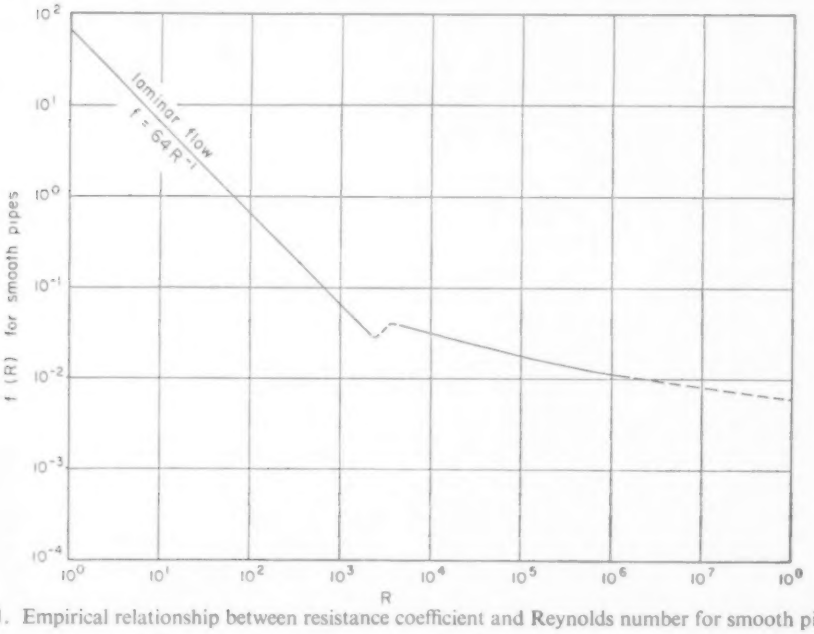

Fig. 1. Empirical relationship between resistance coefficient and Reynolds number for smooth pipes.

This pressure difference is balanced by friction of flow through the tube. The stress τ on the tube's inner surface depends only on the Reynolds number R and the character of the tube's roughness. We shall consider only the case of a perfectly smooth tube. The relation is usually expressed in the form

$$\tau = \tfrac{1}{8} f(R)\, \rho v^2 \tag{5}$$

where $f(R)$ is called the " resistance coefficient " (see, for example, ROUSE, 1938). The empirical relationship between resistance coefficient for smooth tubes and Reynolds number is shown in Fig. 1. The total pressure drop resulting from flow resistance, $\Delta p = 2L\tau/r$, must be equated to expression (4) to determine the flow rate, but first the temperature profile in the ocean must be specified.

The simplest temperature profile is the case of constant temperature down to the tube's tip, which is just immersed in water of lower temperature. Accordingly, we take

$$\theta(y) = \theta_0 \qquad \text{for} \qquad 0 < y < h$$

$$\theta(h) = \theta_h$$

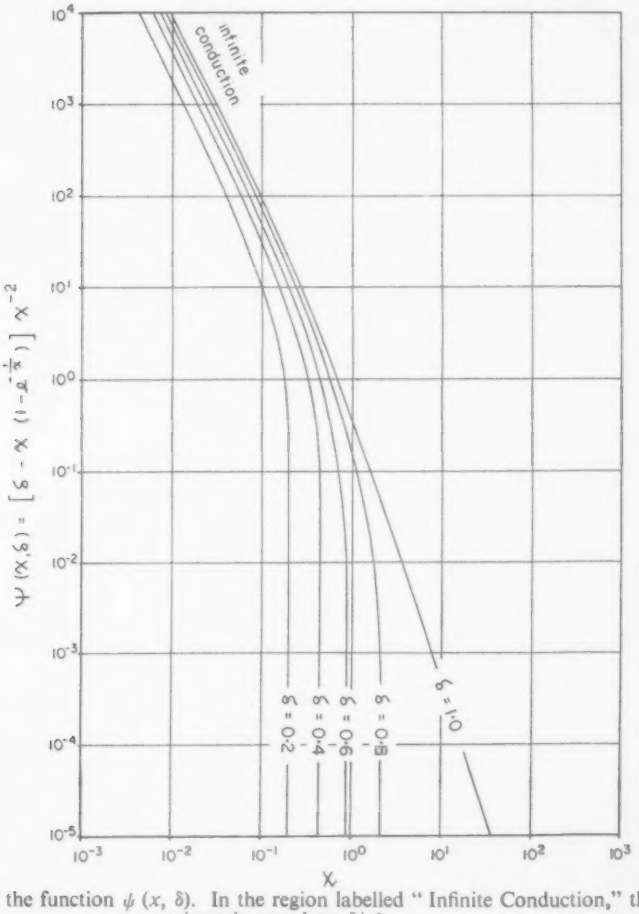

Fig. 2. Plot of the function $\psi(x, \delta)$. In the region labelled " Infinite Conduction," the function is approximately equal to δ/x^2.

For this case the salt fountain will flow perpetually only in the upward direction. Relations (3), (4) and (5) then give

$$f(R) = \alpha^2 \beta \psi(x, \delta) \tag{6}$$

where

$$\psi(x, \delta) = x^{-2}\left[\delta + x\left(e^{-1/x} - 1\right)\right] \tag{7}$$

and

$$x = \alpha R, \qquad \alpha = w\rho cv/4nL$$

$$\beta = \frac{16\, gr^3}{\nu^2}\frac{h}{L}\left(\frac{\Delta\rho}{\rho}\right)_{\theta_h} \qquad \delta = \left(\frac{\Delta\rho}{\rho}\right)_S \Big/ \left(\frac{\Delta\rho}{\rho}\right)_{\theta_h}$$

$$\left(\frac{\Delta\rho}{\rho}\right)_S = \frac{\bar{S} - S(h)}{\rho}\frac{\partial\rho}{\partial S}, \qquad \left(\frac{\Delta\rho}{\rho}\right)_\theta = -\frac{\theta_0 - \theta_h}{\rho}\frac{\partial\rho}{\partial\theta}, \qquad \bar{S} = \frac{1}{h}\int_0^h S(y)\,dy$$

In order for the fountain to work we must have $\delta > 0$, and for stability we must have $\delta < 1$. The function $\psi(x, \delta)$ is shown plotted in Fig. 2. Equation (6) shows that the flow is determined by the three nondimensional parameters, α, β, δ only. The equation is solved graphically for the Reynolds number R very easily for any given set of the parameters α, β, δ by overlaying the plots in Figs. 1 and 2. The following table of values of R was constructed in that way :

Table 1. *Values of Reynolds Number*

α/β	10^5	10^6	10^7	10^8	10^9	δ
					$1{\cdot}1 \times 10^5$	0·2
					$1{\cdot}6 \times 10^5$	0·4
10^{-9}					$2{\cdot}0 \times 10^5$	0·6
					$2{\cdot}3 \times 10^5$	0·8
					$2{\cdot}6 \times 10^5$	1·0
		$2{\cdot}6 \times 10^3$	$7{\cdot}6 \times 10^3$	$2{\cdot}8 \times 10^4$	$1{\cdot}0 \times 10^5$	0·2
		$3{\cdot}2 \times 10^3$	$1{\cdot}2 \times 10^4$	$4{\cdot}2 \times 10^4$	$1{\cdot}6 \times 10^5$	0·4
10^{-8}		$4{\cdot}0 \times 10^3$	$1{\cdot}4 \times 10^4$	$5{\cdot}2 \times 10^4$	$1{\cdot}9 \times 10^5$	0·6
		$4{\cdot}6 \times 10^3$	$1{\cdot}7 \times 10^4$	$6{\cdot}3 \times 10^4$	$2{\cdot}2 \times 10^5$	0·8
		$5{\cdot}2 \times 10^3$	$2{\cdot}0 \times 10^4$	$7{\cdot}1 \times 10^4$	$2{\cdot}6 \times 10^5$	1·0
		$2{\cdot}6 \times 10^3$	$6{\cdot}8 \times 10^3$	$2{\cdot}8 \times 10^4$	$1{\cdot}0 \times 10^5$	0·2
		$3{\cdot}2 \times 10^3$	$1{\cdot}1 \times 10^4$	$4{\cdot}1 \times 10^4$	$1{\cdot}6 \times 10^5$	0·4
10^{-7}		$3{\cdot}8 \times 10^3$	$1{\cdot}4 \times 10^4$	$5{\cdot}2 \times 10^4$	$1{\cdot}9 \times 10^5$	0·6
		$4{\cdot}5 \times 10^3$	$1{\cdot}7 \times 10^4$	$6{\cdot}2 \times 10^4$	$2{\cdot}3 \times 10^5$	0·8
		$5{\cdot}1 \times 10^3$	$1{\cdot}9 \times 10^4$	$7{\cdot}1 \times 10^4$	$2{\cdot}6 \times 10^5$	1·0
	$3{\cdot}0 \times 10^2$	$2{\cdot}5 \times 10^3$	$7{\cdot}4 \times 10^3$	$2{\cdot}7 \times 10^4$	$7{\cdot}9 \times 10^4$	0·2
	$5{\cdot}9 \times 10^2$	$3{\cdot}2 \times 10^3$	$1{\cdot}1 \times 10^4$	$4{\cdot}0 \times 10^4$	$1{\cdot}3 \times 10^5$	0·4
10^{-6}	$8{\cdot}5 \times 10^2$	$3{\cdot}7 \times 10^3$	$1{\cdot}4 \times 10^4$	$4{\cdot}9 \times 10^4$	$1{\cdot}6 \times 10^5$	0·6
	$1{\cdot}2 \times 10^3$	$4{\cdot}5 \times 10^3$	$1{\cdot}7 \times 10^4$	$5{\cdot}9 \times 10^4$	$2{\cdot}0 \times 10^5$	0·8
	$1{\cdot}5 \times 10^3$	$5{\cdot}0 \times 10^3$	$1{\cdot}9 \times 10^4$	$6{\cdot}9 \times 10^4$	$2{\cdot}3 \times 10^5$	1·0
	$2{\cdot}9 \times 10^2$	$2{\cdot}5 \times 10^3$	$6{\cdot}3 \times 10^3$	$1{\cdot}5 \times 10^4$	$2{\cdot}0 \times 10^4$	0·2
	$5{\cdot}8 \times 10^2$	$3{\cdot}2 \times 10^3$	$1{\cdot}0 \times 10^4$	$2{\cdot}5 \times 10^4$	$4{\cdot}2 \times 10^4$	0·4
10^{-5}	$8{\cdot}5 \times 10^2$	$3{\cdot}6 \times 10^3$	$1{\cdot}2 \times 10^4$	$3{\cdot}4 \times 10^4$	$6{\cdot}3 \times 10^4$	0·6
	$1{\cdot}2 \times 10^3$	$4{\cdot}3 \times 10^3$	$1{\cdot}5 \times 10^4$	$4{\cdot}2 \times 10^4$	$1{\cdot}0 \times 10^5$	0·8
	$1{\cdot}4 \times 10^3$	$5{\cdot}0 \times 10^3$	$1{\cdot}7 \times 10^4$	$5{\cdot}1 \times 10^4$	$1{\cdot}3 \times 10^5$	1·0
	$2{\cdot}8 \times 10^2$	$1{\cdot}3 \times 10^3$	$2{\cdot}0 \times 10^3$	$2{\cdot}0 \times 10^3$	$2{\cdot}0 \times 10^3$	0·2
	$5{\cdot}5 \times 10^2$	$2{\cdot}4 \times 10^3$	$3{\cdot}8 \times 10^3$	$4{\cdot}5 \times 10^3$	$4{\cdot}5 \times 10^3$	0·4
10^{-4}	$7{\cdot}9 \times 10^2$	$3{\cdot}0 \times 10^3$	$5{\cdot}6 \times 10^3$	$7{\cdot}9 \times 10^3$	$8{\cdot}9 \times 10^3$	0·6
	$1{\cdot}1 \times 10^3$	$3{\cdot}5 \times 10^3$	$7{\cdot}9 \times 10^3$	$1{\cdot}5 \times 10^4$	$2{\cdot}0 \times 10^4$	0·8
	$1{\cdot}3 \times 10^3$	$4{\cdot}0 \times 10^3$	$1{\cdot}0 \times 10^4$	$2{\cdot}6 \times 10^4$	$6{\cdot}2 \times 10^4$	1·0
	$1{\cdot}3 \times 10^2$	$2{\cdot}0 \times 10^2$	$2{\cdot}0 \times 10^2$	$2{\cdot}0 \times 10^2$	$2{\cdot}0 \times 10^2$	0·2
	$2{\cdot}5 \times 10^2$	$4{\cdot}4 \times 10^2$	$4{\cdot}5 \times 10^2$	$4{\cdot}5 \times 10^2$	$4{\cdot}5 \times 10^2$	0·4
10^{-3}	$3{\cdot}8 \times 10^2$	$7{\cdot}2 \times 10^2$	$8{\cdot}9 \times 10^2$	$8{\cdot}9 \times 10^2$	$8{\cdot}9 \times 10^2$	0·6
	$5{\cdot}2 \times 10^2$	$1{\cdot}3 \times 10^3$	$2{\cdot}0 \times 10^3$	$2{\cdot}1 \times 10^3$	$2{\cdot}1 \times 10^3$	0·8
	$7{\cdot}1 \times 10^2$	$2{\cdot}5 \times 10^3$	$5{\cdot}0 \times 10^3$	$1{\cdot}1 \times 10^4$	$2{\cdot}7 \times 10^4$	1·0
	$2{\cdot}0 \times 10^1$	$2{\cdot}0 \times 10^1$	$2{\cdot}0 \times 10^1$	$2{\cdot}0 \times 10^1$	$2{\cdot}0 \times 10^1$	0·2
	$4{\cdot}4 \times 10^1$	$4{\cdot}5 \times 10^1$	$4{\cdot}5 \times 10^1$	$4{\cdot}5 \times 10^1$	$4{\cdot}5 \times 10^1$	0·4
10^{-2}	$7{\cdot}2 \times 10^1$	$8{\cdot}9 \times 10^1$	$8{\cdot}9 \times 10^1$	$8{\cdot}9 \times 10^1$	$8{\cdot}9 \times 10^1$	0·6
	$1{\cdot}3 \times 10^2$	$2{\cdot}0 \times 10^2$	$2{\cdot}1 \times 10^2$	$2{\cdot}1 \times 10^2$	$2{\cdot}1 \times 10^2$	0·8
	$2{\cdot}7 \times 10^2$	$8{\cdot}7 \times 10^2$	$2{\cdot}6 \times 10^3$	$5{\cdot}0 \times 10^3$	$1{\cdot}1 \times 10^4$	1·0
	$2{\cdot}0 \times 10^0$	$2{\cdot}0 \times 10^0$	$2{\cdot}0 \times 10^0$	$2{\cdot}0 \times 10^0$	$2{\cdot}0 \times 10^0$	0·2
	$4{\cdot}5 \times 10^0$	$4{\cdot}5 \times 10^0$	$4{\cdot}5 \times 10^0$	$4{\cdot}5 \times 10^0$	$4{\cdot}5 \times 10^0$	0·4
10^{-1}	$8{\cdot}9 \times 10^0$	$8{\cdot}9 \times 10^0$	$8{\cdot}9 \times 10^0$	$8{\cdot}9 \times 10^0$	$8{\cdot}9 \times 10^0$	0·6
	$2{\cdot}0 \times 10^1$	$2{\cdot}1 \times 10^1$	$2{\cdot}1 \times 10^1$	$2{\cdot}1 \times 10^1$	$2{\cdot}1 \times 10^1$	0·8
	$8{\cdot}9 \times 10^1$	$2{\cdot}8 \times 10^2$	$8{\cdot}9 \times 10^2$	$2{\cdot}5 \times 10^3$	$5{\cdot}0 \times 10^3$	1·0

The five R values listed for each pair of α, β values corresponds to δ values of 0·2, 0·4, 0·6, 0·8, 1·0, respectively, reading from top to bottom. The mean flow velocity v or volume rate of flow Q can be found from the definition of the Reynolds number ; we have

$$v = \frac{\nu}{2r} R, \qquad Q = \frac{\pi}{2} r\nu R \tag{8}$$

For a large range of values the flow is laminar ($R < 2{,}000$), and also for a large range of conditions the flow of heat into the tube is so fast compared to the fluid velocity up the tube that the temperature of the water inside the tube is essentially equal to that of the outside sea-water. For these conditions to be fulfilled, we must have

$$\beta\delta < 1{\cdot}3 \times 10^5, \qquad \alpha\beta < 6 \tag{9}$$

respectively. The Reynolds number is then given by the simple expression

$$R = \beta\delta/64$$

which enables one to extend the range of computations beyond that encompassed by Table 1.

To take a numerical example, consider a copper tube ($n \simeq 1{\cdot}0$ cal cm deg^{-1} sec^{-1}) with

$h = 300$ m	$\nu = 0{\cdot}01$ cm^2 sec^{-1}
$L = 600$ m	$S - S(h) = 0{\cdot}5$ parts per mil
$w = 2{\cdot}0$ mm	$\theta_0 - \theta_h = 6°$C
$\rho = 1{\cdot}0$ gm cm^{-3}	$\partial\rho/\partial\theta = -2 \times 10^{-4}$ gm cm^{-3} deg^{-1}
$c = 1{\cdot}0$ cal gm^{-1} deg^{-1}	$\partial\rho/\partial S = 7 \times 10^4$ gm cm^{-3} per part per mil
$r = 10$ cm	$g = 10^3$ cm sec^{-2}

We then compute

$$\left(\frac{\Delta\rho}{\rho}\right)_S = 3{\cdot}5\times10^{-4}, \quad \left(\frac{\Delta\rho}{\rho}\right)_\theta = 12\times10^{-4}, \quad \alpha = 8{\cdot}3\times10^{-9}, \quad \beta = 9{\cdot}6\times10^7, \quad \delta = 0{\cdot}29$$

The first (laminar flow) condition (9) is not satisfied. Taking $\alpha = 10^{-8}$, $\beta = 10^8$ and interpolating for δ in Table 1, we arrive at the estimate, $R = 3{\cdot}5 \times 10^4$, $v = 17{\cdot}5$ cm sec^{-1}, $Q = 5{\cdot}5$ litres per sec. This is an impressive rate of flow, resulting largely from the intense salinity minimum assumed.

Let us consider the rate at which the total mass of fish might increase in a nutrient-starved reservoir equipped with a " salt fountain " under the above conditions. We shall assume that phosphorus is the only factor limiting organic production, and that the concentration of inorganic phosphorus at the lower end of the tube (at depth of 300 m) is 2·5 μg atoms/L. It has been estimated (FLEMING, 1940) that the general carbon to phosphorus mass ratio in plankton is 41 : 1. However, a very small portion of the total organic material resulting from the additional flow of phosphorus exists in the bodies of edible fish. Estimates vary widely, but a value of 1 per cent for the ratio of organic carbon in edible fish to total organic carbon falls in the range of probable values. The wet weight of a fish is about 10 times the

weight of its organic carbon (VINOGRADOV, 1953). Then, under the above assumptions, 54 kg/year of edible fish will be " produced " by the addition of 5·5 L/sec of nutrient-rich water. This seems like a small reward for the effort. The same amount of phosphorus could be added by dumping in 290 kg/year of Peruvian guano*, whose phosphorus content is 4·6 per cent (Cia. Administradora del Guano, 1956).

In view of the above example, it appears that STOMMEL *et al.* were correct in describing the perpetual salt fountain as an " oceanographical curiosity."

Acknowledgments—The author is grateful for the advice of Drs. Warren Wooster, Walter Munk and Milner Schaefer.

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*In the above computation, if the tube's radius and wall thickness were 100 cm and 5 mm, respectively, all other conditions remaining the same, the computed flow rate would be about 3,000 litres per second, approximately equivalent to dumping in 160 metric tons of guano per year, and an annual production of 30 tons wet weight of fish.

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Les sédiments precontinentaux profonds dans le Golfe de Gênes

JACQUES BOURCART

(*Received* 15 *June* 1958)

Résumé—Il est classique de dire qu'à partir d'une profondeur de 200 à 300 mètres, les sédiments de la Méditerranée sont des vases bleues calcaires. Les dragages des cañons sous-marins ont pourtant partout donné, sous une mince couche de vase, des graviers ou même des galets qui, à Nice, se poursuivent jusqu'à 2000 mètres. En outre, au bas de la pente continentale, ici rocheuse, un large *glacis*, modelé en marches d'escalier, fait le passage à la plaine abyssale entre 2000 et 2700 mètres environ. Il semble s'étendre tout le long du Golfe de Gênes sur les côtes niçoice, ligure et corse. Les carottages et dragages montrent qu'il est *essentiellement fait de sables grossiers* à faciès continental avec beaucoup de bois et quelques Ptéropodes et Foraminifères. Ces sables se poursuivent par traînées dans la vase abyssale. Comme ceux de la côte algérienne, ils ne sauraient être attribués qu'à des courants de turbidité.

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ON sait, depuis les recherches de Böggild (Expédition danoise du *Thor*) que les sédiments de la plaine abyssale en Méditerranée sont des boues bleues (à moins de 30% de CO_3Ca) et des boues blanches (à plus de 30%) capricieusement mêlées.

Dans un précédent article de cette revue (*Deep Sea Research* 1954, I, p. 126-130), j'ai donné les caractéristiques de ces boues bleues et montré leur profonde analogie avec les "vases du large" et même avec les "vases côtières" du plateau continental, telles qu'elles ont été définies en 1894 par Pruvot. Les vases côtières, dans le Golfe du Lion, dans le Golfe de Gascogne et sur le plateau continental marocain sont séparées des vases du large par les " sables et graviers du large," formation essentiellement biogène, résidu du triage par des courants, qui renferme le plus souvent une faune quaternaire froide (à *Cyprina islandica*), d'âge würmien (BOURCART 1953, 1955a, 1957a, 1958).

Dans la Baie des Anges (Nice), la vase côtière remonte jusqu'à 30 m et, dans la Baie de Villefranche, à 60 m. Elle est là en continuité avec la vase du large qui, comme l'ont montré jusqu'ici tous les carottages, se poursuit jusqu'à 2.000 m. On pensait, jusqu'à présent, qu'elle se poursuivait jusqu'aux plaines abyssales.

Au cours de ces dernières années, des formations grossières, d'origine certainement fluviatile (ce que démontrent à la fois leur morphoscopie et leur composition pétrographique) ont été draguées ou carottées dans les très nombreuses vallées sous-marines qui accidentent le précontinent* de la France métropolitaine :

(1°) *Rech Lacaze-Duthiers* (Port Vendres), entre 300 et 750 m : graviers polis à faune froide, sous 50 cm de vase grise.

(2°) *Cañon de Sète* : à 350 m, poudingue de gros graviers, mal consolidé, avec faune froide.

(3°) *Tête du cañon du Rhône* à 120 m et 180 m : sables grossiers et granules.

(4°) *Cañon de la Cassidagne* entre 300 et 200 m : gros graviers et galets avec roches du bassin de la Durance et coquilles de la faune froide.

*Dénomination globale du plateau continental (*shelf*), de la pente (*slope*) et du glacis (*rise*).

(5°) *Vallée de Sicié* (Toulon), de 500 à 100 m : conglomérat argilo ferrugineux avec roches étrangères à la région ; sur les bords de la vallée, un gravier analogue, emballé dans les limons rouges, est inclus dans les lapiés du calcaire sableux du Quaternaire ancien qui forme la dalle recouvrant le plateau.

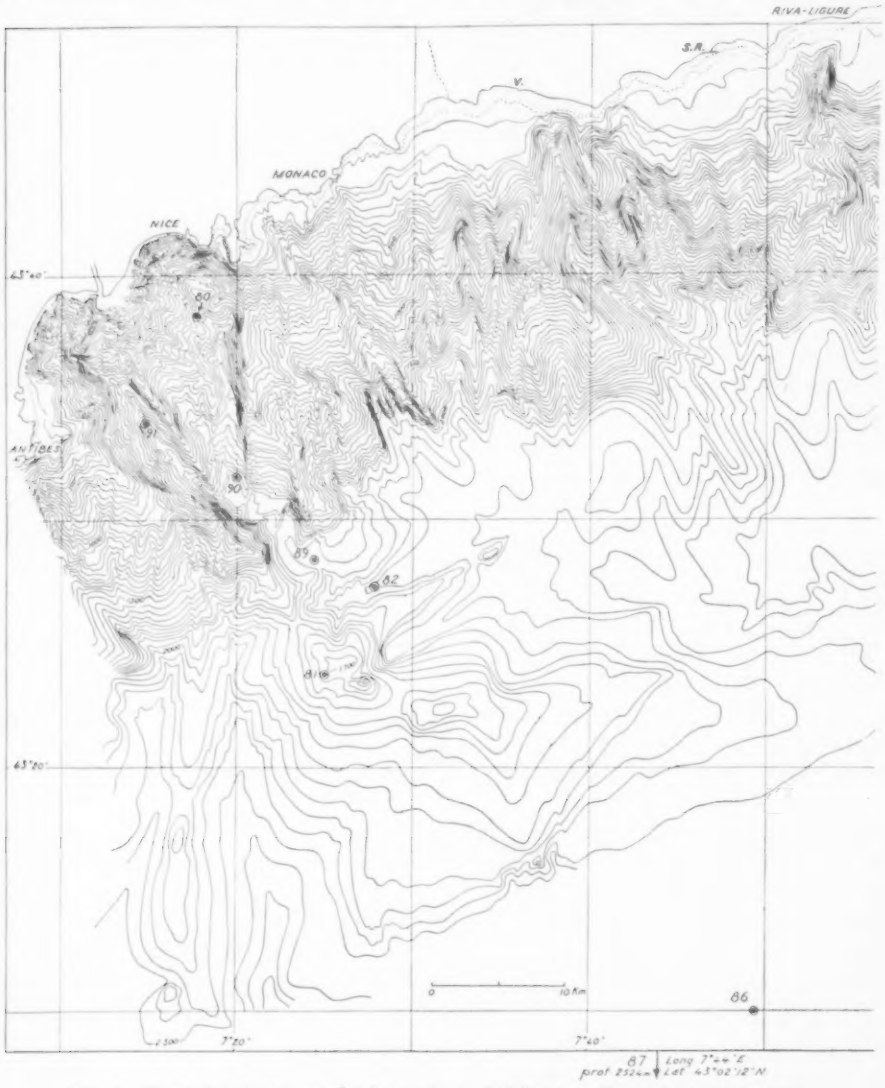

Fig. 1. Carte des régions profondes au large de Nice ⊙ : Dragages et carottages.

(6°) *Vallée de Saint-Tropez*, entre 300 et 200 m : galets pouvant atteindre 5 cm de grand axe ; leur morphologie et leur pétrographie montrent qu'ils sont d'origine certainement fluviatile.

(7°) *Cañon de la Brague* (*Baie des Anges*), entre 400 et 200 m : galets pouvant atteindre 5 cm, de forme et de nature analogues à ceux du cordon littoral ou de la partie inférieure de la rivière subaérienne.

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(8°) *Cañon du Var* : gravier de 2 cm.

(9°) *Cañon du Paillon* (*Nice*) : gravier atteignant 2 cm, carotté à 150 m sous 15 cm de vase bleue.

(10°) *Carottages sur les flancs du pays continental submergé corso-ligure* : de 180 à 250 m : sable organogène, recouvert vers 310 m de vase bleue ; sur le flanc d'un cañon : vase grise ; dans le fond d'un cañon : sable organogène, mêlé d'éléments de schistes lustrés (le pays corso-ligure est fait de calcaires du Miocène supérieur, reposant vraisemblablement sur un socle de schistes lustrés).

(11°) *Soubassement de l'Ile de Capraïa* : sables grossiers, formés d'éléments de schistes lustrés, descendant jusqu'à 500 m. Ces sables, sans calcaire, renferment de très nombreux moules de Foraminifères en glauconie et en silice.

(12°) *Cañon de Saint-Florent* (Corse) : vase sur les parois ; dans le fond, à 310 m : sables organogènes avec coquilles mortes et débris de coraux buissonnants fossiles.

(13°) *Détroit de Bonifacio*: galets granitiques dans les zones profondes (60 à 70 m).

J'ai décrit, en 1953, des sables néritiques, très riches en minéraux lourds et en fragments de roches provenant certainement du continent avec un mélange de microfaunes froide et chaude et des fragments de bois ferruginisés à 2750 m de profondeur au large de Bougie en Algérie. H. Pettersson avait recueilli des sables analogues à 2500 et 2750 m, immédiatement au large d'Alger. De tels sables ne peuvent être interprétés que comme provenant de deltas sous-marins dûs à des courants de turbidité.

Dans toutes les carottes qui ont été faites dans les cañons, le gravier est soit à nu, soit sous de la vase ; celle-ci contient la faune froide qui en est parfois dégagée, mais est toujours vasicole ; mais il semble que parfois, on atteint une vase dure, plus ancienne*.

Dans la région de Nice, l'âge des graviers et galets n'est pas déterminé avec certitude; mais il semble qu'il repose partout sur une vase très compacte à *Leda*, *Nucula striata et Nassa Edwardsi* qui a été retrouvée par les forages de l'aérodrome de la Californie et qui affleure, immédiatement sur la rive droite du Var, le long de la route de mer. Elle y est recouverte par les limons rouges grimaldiens et leur cailloutis de base. De Toulon à Port-Vendres, les cañons sont entaillés dans des grès très littoraux qui sont, manifestement, comme nous l'avons vu, antérieurs aux limons rouges et, probablement, assimilables au Tyrrhénien compris dans un sens très large.

Le remplissage des cañons sur toute la côte métropolitaine de la France semble donc être fluviatile au moins jusqu'à 600 m et dater du grand intervalle régressif, précédant la dernière glaciation, que j'ai appelé Grimaldien. Aucun dragage, aucun carottage plus profond, n'avait donné jusqu'ici autre chose que de la vase bleue. Cependant un carottage fait dans le grand élargissement de la rivière de Nice, immédiatement au Sud du Cap de Nice, vers 900 m de profondeur, avait ramené une vase bleue extraordinairement compacte, sans microfaune caractéristique, mais semblant plus ancienne que les " vases du large." En outre, la grande vallée de Toulon paraissait, d'après nos levés, se terminer par un grand delta entre 2200 et 2300 m.

L'idée que des sédiments grossiers d'origine continentale ont pu être transportés par les cañons jusqu'à de pareilles profondeurs au cours du Quaternaire moyen, peut paraître aventureuse. Mais les résultats des carottages qu' ERICSON, EWING

*C'est cette vase dure qui, comme l'ont vu les divers passagers du Bathyscaphe F.N.R.S.3, forme des énigmatiques cônes sur le fond.

et HEEZEN (1948) ont faits à bord de l'*Atlantis* dans le grand cañon de l'Hudson, peuvent appuyer cette interprétation. L'Hudson est en gorge jusqu'à 150 milles au large du rebord continental vers 2500 m. Les parois du cañon creusé, dans le Mio-pliocène, ne sont recouvertes que par un peu de vase molle. Les carottes, dans le fond du cañon contiennent du gravier avec beaucoup de coquilles quaternaires ayant vécu à des profondeurs variées, mais souvent faibles. En dehors du cañon, l'Hudson sous-marin se poursuit par une sorte d'immense delta où des échantillons de sables ont été obtenus entre 4370 et 4940 m. Ce sable, avec *graded bedding*, repose sur des argiles rouges abyssales ; il est, en général, recouvert par 50 cm de vase à Foraminifères. Les auteurs pensent qu'ils ont traversé des sédiments allant de la fin du dernier interglaciaire (Sargamon) à la fin du Wisconsin (Würmien).

Les récents travaux de notre équipe en Méditerranée, nous paraissent montrer que l'étendue des formations deltaïques datant de la dernière grande régression est beaucoup plus grande qu'on ne le pensait jusqu'ici. Récemment J. Y. Cousteau avait attiré notre attention sur le fait que le glacis, docement incliné, qui fait suite à la pente continentale très raide, vraisemblablement jurassique, a sa surface modelée en sorte de dunes très régulières dont le versant abrupt est tourné vers le large. Ces sortes de " dunes " sur la côte niçoise recouvrent d'abord un pays de collines dont les sommets sont revêtus de vase molle.

Dans toute cette étendue, en général entre 2200 et 2600 m, les carottages effectués (voir la liste ci-dessous), soit dans la profonde vallée de Nice, soit entre les reliefs, soit sur le glacis paraissant uniforme, nous ont donné des sables gris, en général assez grossiers, quartzeux et très micacés et contenant des petits fragments de pélites rouges du Trias des enveloppes du Mercantour. Ces sables sont absolument identiques non seulement à ceux qui surmontent les galets ou graviers dans la partie inférieure des cañons, mais même à ceux du Var actuel. Ils contiennent beaucoup de bois flottés dans la vallée de Nice et partout des fragments de Ptéropodes ainsi que par nids, des accumulations de Globigérines et Orbulines. Il semble que le grand delta de la rivière de Nice soit coalescent avec ceux de toutes les vallées qui descendent du précontinent au moins jusqu'à la frontière italienne. Un même lit de déjections parait recouvrir toute la base de la Corse occidentale et du haut-fond corso-ligure.

Dans le but de prélever une carotte, soustraite aux influences continentales, qui puisse nous servir d'étalon pour déterminer le taux de sédimentation dans le Golfe de Gênes, nous avons carotté au sud des derniers reliefs qui émergent du glacis à 2524 et 2690 m. Le première carotte ne nous a encore donné que des sables gris très fins, plus ou moins vaseux ; la seconde a recueilli 3 m, 50 de vase grise, mais entremêlée de flammes constituées par le même sable que la première carotte.

L'aspect de cette carotte de la plaine abyssale est exactement la même que celle des carottes que nous avions prélevées (BOURCART et OTTMANN, 1957) dans les cours supérieurs du Var et du Paillon sous-marin. Nous y attribuions ces passées de sables à des courants de turbidité qui se seraient produits après les importantes crues de ces deux fleuves. Dans le cas des carottes prélevées en dessous de 2500 m, il paraît plus difficile de faire appel à des courants de turbidité actuels, à moins que ceux-ci soient dûs, comme ceux que nous avons étudiés avec L. Glangeaud-lors du relevage des câbles rompus à la suite du tremblement de terre d'Orléansville, à des éboulements du talus sous-marin consécutif aux séismes. La forme en marches

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d'escalier, ressemblant à des dunes, mais chacune plus basse que la précédente, évoque, plutôt que des rides, celle que prend un écoulement visqueux.

En tout état de cause, nous devons admettre que, dans le Golfe de Gênes, au delà des vases du large, une importante bande de sable, tout à fait différente des sables trés coquillés du Plateau continental, précède la vase abyssale à peu près uniquement planctonique. Il semble que ces sables datent de la dernière fusion des glaciers de montagne. Cette bande de sables est comparable à celles, beaucoup plus importantes, qui ont été décrites sur le bord de l'Atlantique occidentale ou de l'Alaska.

Il reste à expliquer par quel mécanisme, ces sables ne sont pas entièrement ensevelis sous les vases qui se déposent sur toute une partie de la pente continentale et presque jusqu'au littoral dans les baies profondes, comme celle de Nice.

Les sables profonds du glacis contiennent toujours des éléments planctoniques, malgré leur aspect absolument terrigène : ce sont en général des Ptéropodes, des Globigérines et des Orbulines. Tout se passe comme si ces éléments étaient enfouis soit par les sables constamment remaniés en surface, soit par des courants de turbidité, soit simplement par la descente de toute la masse. C'est la fraction grossière des éléments pélagiques qui est surtout conservée ; les particules fines semblent ne pas se déposer par suite d'une turbulence de l'eau du fond.

La bande de vase qui succède aux sables profonds dans les moindres profondeurs, n'est pas, elle non plus, d'origine exclusivement planctonique. Aux éléments pélagiques, à peu près exclusivement calcaires en Méditerranée (débris de Foraminifères et de Coccolithophoridées), s'ajoutent beaucoup d'éléments flottés terrigènes : de très nombreuses paillettes de micas et de chlorite et même des grains de quartz de près d'un millimètre qui ont été transportés enrobés d'air (BOURCART 1955 b).

Ces éléments flottés semblent de plus en plus nombreux au fur et à mesure que l'on se rapproche de la côte, aussi bien à la surface qu'entre deux eaux. Tout semble se passer comme dans un estuaire ou dans un port d'une mer à marée : le débit flotté est à peu près uniquement porté vers l'amont par le flot ; une très faible partie seulement revient par le jusant. Il en est ainsi des touffes d'algues arrachées par la tempête ou des paquets d'écume qui, dans la Rance, s'agrègent au fond de l'estuaire jusqu'à former un véritable pack. Tous les détritus flottés, les plumes d'oiseaux et même les animaux pélagiques comme les méduses se dèplacent à peu près uniquement vers l'amont. Le phénomène est particulièrement impressionnant dans la Baie du Mont Saint-Michel où l'on voit, à marée montante, l'eau devenir de plus en plus trouble à mesure que l'on se rapproche du littoral. Tout le débit solide augmente au fur et à mesure que la profondeur, c'est à dire le volume d'eau, diminue.

En Méditerranée, où la marée est insignifiante, il semble que pourtant tous les courants aient, en général, une composante dirigée vers la côte. Ainsi s'expliquerait l'atterrissage final d'à peu près tous les objets flottants abandonnés au large.

La concentration en débit solide augmente non seulement vers la côte, mais aussi vers le fond. Quand elle a dépassé une certaine limite, les particules s'agrègent les unes aux autres et revêtent le fond de cette vase, initialement ultra-thixotropique, que nous avons étudiée dans la Rade de Villefranche. Comme dans les estuaires, cette vase molle a tendance à revêtir aussi le relief profond et, notamment, les parois des cañons. Sous l'action du simple frottement de son guide-rope, le Bathyscaphe FNRS 3 l'a remise entièrement en mouvement.

Cette vase nouvelle s'accumule particulièrement dans les baies profondes, partout où il n'y a pas de courants de retour.

Le dépôt centrifuge de vase peut alterner avec ceux de courants de fonds centripètes, comme les courants de turbidité qui sont provoqués par les crues des fleuves côtiers ou les éboulements des talus de sables. Ce sont eux qui sont la cause des intercalations en flammes ou nids de sable aussi bien dans la vase côtière que dans la vase profonde (BOURCART, *et al.* 1957).

Cette explication a encore évidemment un caractère entièrement hypothétique. Mais nous avons l'intention, au cours des prochaines campagnes, d'essayer de capturer systématiquement, à l'aide de bouteilles horizontales ou de *silt-samplers*, ce débit solide transitant au voisinage du fond.

LISTE DES ECHANTILLONS
(CAMPAGNE CALYPSO 1958)
Carottages (C) et Dragages (Dr.)

C 80 Position : 43° 38′ 20″N, 7° 17′ 13″E — Vallée de Nice (élargissement)
Profondeur : 950 mètres
Longueur : 4 m (tube de 5 m)
Echantillons : 4 sections numérotées I à IV de la base à la surface
Vase gris-bleu, très molle en surface

C 81 Position : 43° 23′ 55″N, 7° 24′ 55″E — Relief paléozoïque au large de la pente continentale
Profondeur : 2·096 mètres
Longueur : 0 (tube de 2 m)
Echantillon : récolté sur les poids du carottier
Carottier pilote : vase typique
Vase gris-bleu très molle

C 82 Position : 43° 27′ 28″N, 7° 27′ 46″E — Vallée de Nice
Profondeur : 2·014 mètres
Longueur : 0 (tube de 7 m)
Echantillon : récolté dans l'ogive Sable fin de couleur générale grise

Dr. 83 Position : 43° 27′ 28″N, 7° 27′ 46″E — Dragage
Profondeur : 2·014 mètres
Echantillons : I Total
II lavé
III tamisé (mailles de 0·8 mm)
IV petit tube accessoire
Sable vaseux fin, micacé, avec nombreux grains rouges ; couleur générale noirâtre ; nombreux débris ligneux ; Ptéropodes ; le sable est en mottes, il semble que la surface soit de la vase.

C 86 Position : 43° 10′N, 7° 49′ 30″E — Dans la plaine abyssale au large du relief supposé paléozoïque
Profondeur : 2·690 m
Longueur : 3 m 50 (tube de 7 m)
Echantillons : 4 sections I à IV de la base à la surface
Vase sableuse avec des passages très sableux (sable fin) couleur : gris sombre

C 87 Position : 43° 02′ 12″N, 7° 44′E — Au voisinage du glacis de Nice
Profondeur : 2·524 mètres
Longueur : 1 m 50 (tube de 7 m)
Echantillons : 2 sections I et II (surface)
Sable fin plus ou moins vaseux de couleur générale gris foncé

C 89 Position : 43° 28′ 20″N, 7° 24′ 30″E — Confluent de la vallée du Var et de celle du Paillon = Vallée de Nice
Profondeur : 1910 mètres
Longueur : 1 m, 50
Echantillons : 8 sacs numérotés I à VIII, VIII étant la partie supérieure
Partie inférieure : gravier et petits galets
Partie supérieure : sable fin noirâtre avec grains rouges

C 90 Position : 43° 31′ 45″N — Vallée sous-marine du Var
7° 20′E
Profondeur : 1635 mètres
Echantillons : 1 sac
1 gros galet (6 cm) coincé dans l'ogive et quelques petits graviers parfois recouverts d'une mince couche de vase

C 91 Position : 43° 34′N — Vallée sous-marine du Var
7° 14′ 45″E
Profondeur : 1·335 mètres
Longueur : 1 m, 20
Echantillons : 5 sacs numérotés I à V, V étant la surface de la carotte
Partie inférieure : gravier et petits galets
Partie supérieure : sable noirâtre

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Measurements with the carbon-14 technique of the respiration rates in natural populations of phytoplankton

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(*Received* 14 *April* 1958)

Abstract—A method for measuring the rate of respiration of a phytoplankton population by means of the carbon-14 technique is described. A curve showing the rate of net photosynthesis as a function of light intensity is obtained. By extrapolation the rate of respiration is deduced.

The accuracy of the method is discussed on a theoretical as well as on an experimental basis.

From 78 measurements made during the summers of 1956 and 1957 in the North Atlantic and in the Arctic, 90 per cent of all rates measured were 15 per cent or less of light-saturated photosynthesis, 68 per cent were 10 per cent or less. In not a single case did the rate of respiration reach anywhere near the order of magnitude obtained in light-saturated photosynthesis. This was also the case with 12 similar measurements made during the *Galathea* Expedition, mainly in tropical waters.

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(1) INTRODUCTION

IN order to evaluate the primary production by the plankton algae in a natural habitat it is necessary to know both the size of the gross production and the size of the net production. Therefore the rate of respiration must be known also.

Gross production — respiration = net production.

With cultures of plankton algae it is easy by many different techniques to measure both the rate of gross production and the rate of net production. All techniques in which the metabolism of either oxygen or carbon dioxide is measured are applicable. The metabolism has to be determined both in the light and in the dark. If healthy fast growing cultures are used they apparently need not necessarily be free of bacteria. The rate of respiration in bacteria is a minor part of the total respiration in such cases.

In a water sample from a natural habitat in the sea or in a lake the part of the respiration due to the autotrophic algae is by no means the only important one. Besides bacteria, many other heterotrophic plants may be found. Finally zooplankton organisms may contribute considerably to the total respiration.

In experiments with the usual dark and light bottle oxygen method under conditions where this method is applicable, it is possible to measure the rate of gross production by the autotrophic phytoplankton and the rate of respiration in all of the organisms present in the water sample. It is, however, impossible to obtain a value for the true net production, i.e. (net primary production). We measure instead the value : gross production in the plants — respiration in all of the organisms present = net community production. The relation : net primary production : net community production varies from a value only slightly above one upwards.

It was shown briefly by STEEMANN NIELSEN and JENSEN (1957 p. 102) that values of respiration in the phytoplankton exclusively may be obtained by using the carbon-14 technique to measure primary production. To measure the rate of respiration in

phytoplankton a series of experiments must be made showing the rate of net photosynthesis as a function of light intensity. By extrapolation of the light intensity to 0, the rate of respiration can be obtained.

In the present article the method is described in more detail and the accuracy is discussed. Further, we present an extensive account of the respiration measurements obtained during cruises of the Danish research vessel *Dana* in the North Atlantic and in the Arctic 1956-57.

(2) THE TECHNIQUE USED FOR MEASURING THE RATE OF RESPIRATION

The carbon-14 technique for measuring organic production in the sea was originally described by STEEMANN NIELSEN (1952). There has been some disagreement concerning the value measured by it. RYTHER (1954) favoured net production in contrast to the present writer, who considers the measurements to represent something between net and gross production. As RYTHER used an experimental time of 24 hours while the present writer used only a few hours the discrepancy is easily explained. In experiments of very long duration the carbon-14 technique is bound to measure net production. Under such conditions practically the same relative proportion is found between ^{14}C and ^{12}C in the water and in the algae during the greater part of the experiments. Thus the method resembles in fact an ordinary chemical technique measuring the net-uptake of carbon dioxide.

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However, in experiments of short duration, only about 50-70 per cent of the CO_2 produced – or expected to be produced – by respiration is in some way or other identical with CO_2 fixed during photosynthesis as experimentally shown by STEEMANN NIELSEN (1955). The percentage is about the same at a high and at a low light intensity. In experiments of short duration the carbon-14 technique thus measures something between net and gross production. To obtain values of either of these two quantities, it is necessary to make a correction. A proper correction is possible only if the rate of respiration is known. STEEMANN NIELSEN (1952) and STEEMANN NIELSEN and JENSEN (1957) arbitrarily made the correction assuming the rate of respiration to be 10 per cent of the photo-synthetic rate at optimum light intensity.

In plankton collected in Nature only relatively short experimental periods can be normally employed. The enclosure of a water sample in a bottle of glass is an artificial interference and must be of short duration only. All of the experiments described in this paper were of short duration, a maximum of four hours.

Unless otherwise mentioned, the technique is the same as that described by STEEMANN NIELSEN and JENSEN (1957). The filtration of the samples was made under pressure using the apparatus illustrated by STEEMANN NIELSEN (1958a) Fig. 1. For collecting the water samples a water bottle made by Laboratoire Hydrographique, Copenhagen, was used, similar to Knudsens insulated water bottle but with all of the parts in contact with the water sample made of nylon.

The experiments to demonstrate the method are illustrated in Fig. 1. These were made in Copenhagen under ideal experimental conditions in the laboratory, using a rapidly growing culture of *Chlorella vulgaris*. Each experiment lasted four hours. Measurements were made in duplicate at many different light intensities. The light intensity was varied by using a series of neutral filters from Schott and Genossen, which met all requirements.

The solid line shows the rate of photosynthesis (uncorrected) as a function of light energy. Only the measurements at low light intensities are given. The rate of dark fixation has been subtracted. The curve is undoubtedly a straight line as is to be expected theoretically at low light intensities. The intersection between the curve and the abscissa is at 375 lux.

If the uncorrected measurements represent net production such as proposed by RYTHER (1954), the compensation point would be at 375 lux and the respiration rate would be 5·4 per cent of the optimum rate of photosynthesis. The respiration rate is found by extrapolating the linear part of the photosynthetic curve back to the intersection with the ordinate.

As mentioned above, in experiments of short duration, the interference between respiration and photosynthesis only accounts for about 60 per cent of the carbon dioxide. Consequently, the real respiration rate is about 10/6 of that obtained directly. The curve for net production is found by drawing a line parallel to the original curve but intersecting the ordinate at a point representing the true respiration rate (dashed line in Fig. 1). Thus, the real respiration rate is 8·6 per cent of the optimum rate of photosynthesis and the compensation point is 600 lux. If no correction is made in experiments of short duration the value for the respiration rate will be somewhat too small. In experiments of very long duration – such as the 24 hours used by RYTHER – no correction need be made.

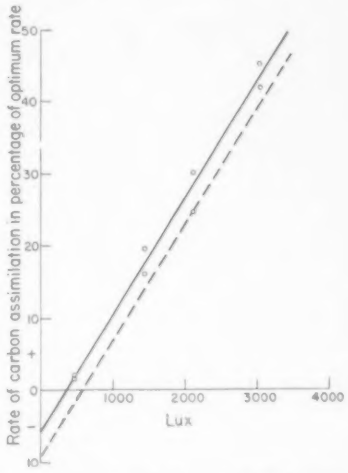

Fig. 1. Rate of photosynthesis as a function of light intensity. *Chlorella vulgaris*. Temperature 22°C. The dashed line presents the corrected values.

The experiments on the *Dana* were made in a small room below deck. The water bath used was made of concrete and asbestos, with a glass window in front. The water could be adjusted to all temperatures down to 3°C. It was possible to shift rather rapidly from one temperature to another. The temperature was constant to 0·5°C. Rapid circulation of sea-water prevented any important effect of the heat from the incandescent bulb illuminating the front window.

Six 60 ml bottles were placed on a rotating disc in the centre of the water bath. These were illuminated by 9 60 or 100 watt bulbs placed on a plate covered with reflecting foil in front of the window.

Light intensity was varied by using neutral filters placed in front of the bottles and in some instances by placing reflecting foil behind the bottles. Although Schott and Genossen have a fine series of filters meeting all requirements, these could not be used with the relatively large bottles employed (60 ml), as the maximum size of the filters – if not specially manufactured – is 40 × 60 mm. In the present studies on the *Dana*, 3 filters from Chance Brothers were used, ON 31, ON 32 and ON 33. The first two of these absorbed 61 and 78 per cent of the light respectively independent of the wave-length. This is only approximately true for ON 33 which absorbed 36 per cent of the light. It was used only during 1956. Each special filter plate must be separately checked, as it is not possible to rely on their general characteristics.

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In 1956, an additional old neutral filter of unknown origin was used which absorbed 87 per cent of the light.

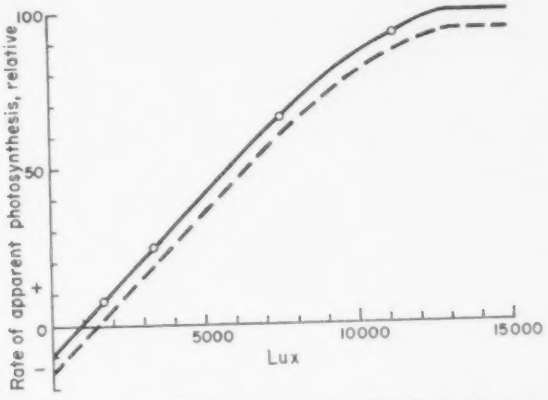

Fig. 2. Rate of photosynthesis as a function of light intensity. The dashed line presents the corrected values. Surface plankton. *Dana* Station 10561, July 22 1957. Davis Strait 69° 40′N, 54° 40′W. Temperature 6°C.

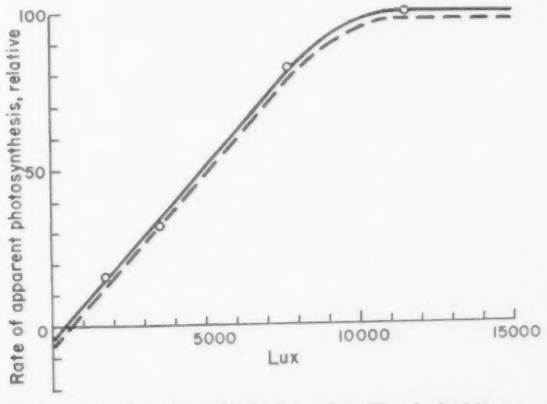

Fig. 3. Rate of photosynthesis as a function of light intensity. The dashed line presents the corrected values. Surface plankton. *Dana* Station 10531, July 16, 1957. Davis Strait, 63° 35′N, 56° 40′W. Temperature 6°C.

The light absorption of the neutral filters must be constant over all the spectrum where photosynthesis takes place and where the photocell is sensitive to light. The condition is essential if incandescent light with maximum energy in the red and infra-red part of the spectrum is used. A part of this light not used in photosynthesis is registered by an ordinary photocell. Deviations from a constant light absorption by neutral filters are often found in this very part of the spectrum.

The size of the wheel in the water bath employed in the present investigations made it possible to put a maximum of 6 bottles on it. One bottle was covered with a black material and used for measuring dark fixation. Duplicates of the sample illuminated without a filter were employed in all series made during the 1957 cruise.

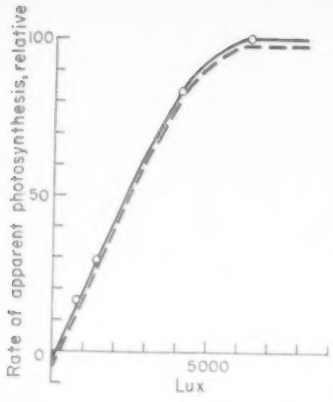

Fig. 4. Rate of photosynthesis as a function of light intensity. The dashed line presents the corrected values. Shade plankton from a depth of 37 m (1% of the green light at the surface). *Dana* Station 9989, July 7, 1956. East Greenland Current, 62° 00'N 41° 07'W. Temperature 5°C.

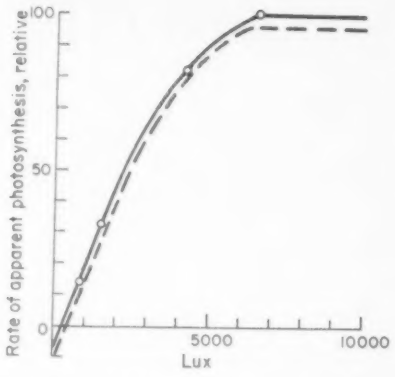

Fig. 5. Rate of photosynthesis as a function of light intensity. The dashed line presents the corrected values. Shade plankton from a depth of 51 m (1% of the green light at the surface). *Dana* Station 9966 June 28, 1956. Atlantic, 62° 00'N, 9° 00'W. Temperature 9°C.

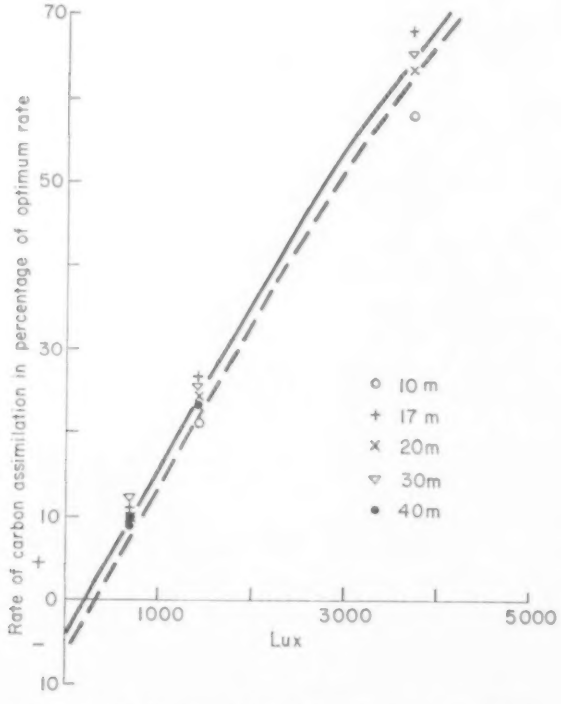

Fig. 6. Rate of photosynthesis as a function of light intensity. The dashed line presents the corrected values. *Dana* Station 10041 July 25, 1956. Godthaab Fjord, Greenland. 64° 07'N, 57° 53'W. Temperature 5°C.

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Only 5 different light intensities (including darkness) are thus available in each series if not duplicated. If the right light intensities are chosen an adequate curve showing the light dependence of photosynthesis is obtained. From the entire area of surface water investigated in summer the following light intensities – besides dark – were found adequate : about 2000, about 4000, about 8000 and about 12,000 lux (Figures 2-3). For water from the lowest part of the photic zone the above mentioned light intensities were rather unsuitable often because photosynthesis ceased to be linear already below 4000 lux (Figures 4-5). In order to obtain the slope of the linear part of the curve, at least two light intensities, preferably three, must be found within the range where photosynthesis increases proportionally with the light intensity. For water from the lowest part of the photic layer the following light intensities were generally found applicable : about 800, about 1400, about 4000 and about 6500 lux. An exception was found in areas where an intense vertical mixing of the water masses within the photic zone takes place. Here the same light intensities are applicable for all water samples since the photosynthesis curves from all depths are practically identical (Fig. 6). No " shade " plankton is found here.

It is impossible to measure photosynthesis with the carbon-14 techniques at or below the compensation point. Preferably the rate of photosynthesis should be double the rate of respiration. A light intensity of only 800 lux is thus in many cases too low when surface samples are used for the experiments. The compensation point is here often found above 600 lux. In samples from the lower part of the photic zone the compensation point nearly always is found definitely below 500 lux. At 800 lux the rate of photosynthesis is thus measured without difficulty.

(3) THE ACCURACY OF THE MEASUREMENTS OF RESPIRATORY RATE

Values derived by extrapolation are fundamentally not as exact as those directly measured. However, the accuracy of the measurements of respiration using the present method is by no means poor if the measurements of photosynthesis have been properly made. Comparing respiratory measurements using either the oxygen technique or the present technique, the accuracy of the latter normally is much higher.

A high precision in measuring photosynthesis with the carbon-14 technique has always been achieved during the Danish expeditions. Poor agreement between duplicates, if not merely occasional, indicates an insufficient control of the technique.

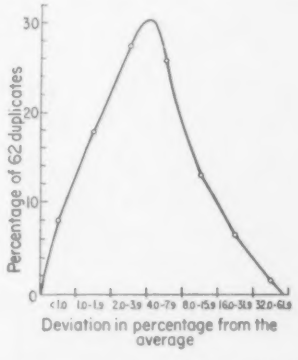

Fig. 7. Deviation of 62 duplicates (measurements of photosynthetic rate).

Fig. 7 shows the deviation in percentage from the average of 62 duplicate measurements of photosynthesis at about 6500 lux obtained during the cruise of the *Dana* in 1957. In 49 pairs (79 per cent) the deviation was below 8 per cent. In 57 pairs (92 per cent) the deviation was below 16 per cent. A high deviation is thus not commonly found. When drawing the rate of photosynthesis as a function of light intensity, single strongly aberrant measurements are easily detected. A great help

is the close similarity of all such curves. Several causes for the occasional occurrence of aberrant values may of course be found.

In Fig. 8 a hypothetical example is presented. The fully drawn line shows the rate of photosynthesis as a function of light intensity computed on the basis of measurements at 1700, 3400, 7500 and 11,200 lux. It is assumed that these measurements are absolutely correct. It is further assumed that the actually measured values, if not completely aberrant, may be a maximum of ± 15 per cent wrong at the higher

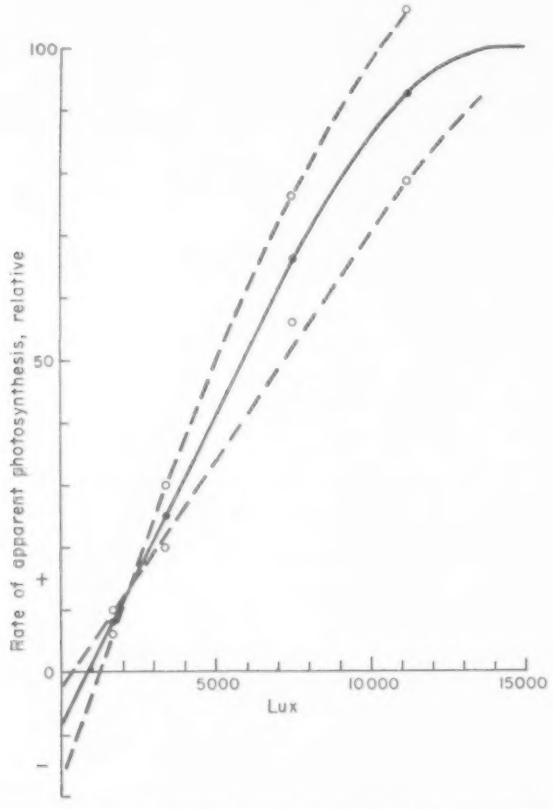

Fig. 8. Rate of photosynthesis, as a function of light intensity. A theoretical example. The two dashed lines represent the two extreme combinations.

light intensities, ± 20 per cent at 3400 lux and + 25 per cent at 1700 lux. The filled circles in Fig. 8 show the maximum deviations. It must be considered as the two extreme combinations when either the measurements at 1700 lux have the maximum negative deviation whereas all of the other measurements have the maximum positive deviation, or when the deviation is maximum in the positive direction at 1700 lux whereas all of the other measurements have the maximum negative deviation. Whereas the rate of respiration according to the correct curve is 8 per cent of the rate of total photo-synthesis, it is 3 and 17, respectively, according to the two dashed curves. In nearly all cases the accuracy will be much better.

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For the present purpose, the accuracy of the measurements which approximate the order of magnitude for the respiration rates must be considered completely satisfactory. At sea, at least, it would be rather inconvenient to use the technique with a much higher precision (Fig. 1).

The measurements made at the mouth of the Godthaab Fjord may serve as a good example of the accuracy obtained on the *Dana*. Due to the strong tidal currents which produce vertical mixing, the plankton algae from all depths receive – integrated for 24 hours – practically the same amount of light energy. Consequently no differences in the shapes of the curves showing the rate of photosynthesis as a function of light intensity are found for water samples collected at different depths. Fig. 6, page 226 presents the results of 5 such series from St. 10041. Water samples were collected from the following depths : 10, 17, 20, 30 and 40 metres. Only the measurements from the three lowest light intensities are presented in the figure. It is possible to draw 5 separate curves, but these are so similar that only a joint single curve is drawn. The dashed curve is drawn after being corrected for the intermixing of photosynthesis and respiration. The rate of respiration according to the joint corrected curve is 5 per cent of the rate of photosynthesis at optimum light intensity. Drawing the curves separately for the different depths, the following rates of respiration were found – in percentage of optimum rate of photosynthesis : 10 m, 7 per cent, 17 m 7 per cent, 20 m 5 per cent, 30 m 2 per cent, 40 m 7 per cent. The value for the photosynthetic rate – 40 m. depth, 3700 lux – is obviously too low. Even if only measurements with water from 40 m had been made, a correct curve could have been readily drawn.

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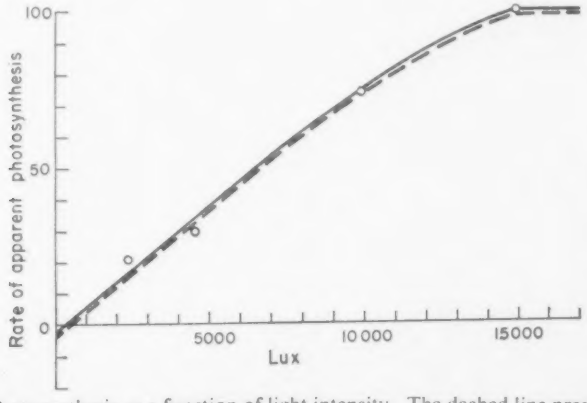

Fig. 9. Rate of photosynthesis as a function of light intensity. The dashed line presents the corrected values. Surface plankton. *Dana* Station 10589, August 13, 1957. Atlantic, 51° 00′N, 29° 30′W. Temperature 15° C.

In the experiments hitherto described no difficulties at all were found when drawing the curves. A strongly aberrant measurement is easily discovered as shown above, but slightly aberrant measurements are a little more difficult to handle. Fig. 9, presents the results from a station in the Atlantic west of Ireland, and shows such a typical example. It is obvious that a straight line joining the measurements at 2300 and 4500 lux does not present the correct slope of the curve. Respiration would be

negative and the curve would not fit with the measurements at the higher light intensities. Measurements at 9900 lux were made in duplicate and they were practically identical. If the measurements at the two lower light intensities are corrected by − 20 per cent and + 15 per cent, respectively (cf. Fig. 8) the curve will fit the measurements. This was done when drawing Fig. 9. If instead the measurements at 2300 lux had been considered aberrant and that at 4500 correct and the curve drawn accordingly, the corrected rate of respiration would have been 11 per cent of the rate of photosynthesis at optimum light intensity instead of the 3 per cent.

Although the difference may seem important, for the ecological evaluation it is by no means decisive. The order of magnitude of the rate of respiration cannot be obscured by a single uncertain measurement. If the carbon-14 technique is properly used, the chance of finding more than a single aberrant value in a series is minimal. It is of course necessary to use such high activities that the counts obtained at the low light intensities are as accurate as those obtained at the high light intensities.

(4) RESPIRATION MEASUREMENTS 1956-57

Fig. 10 presents graphically the scattering of 78 measurements of the rate of respiration according to 78 curves made during the *Dana* cruises 1956-1957 showing the rate of photosynthesis as a function of light intensity. The rate of respiration is given in percentage of light-saturated photosynthesis.

According to Fig. 10, 90 per cent of all respiratory rates measured were 15 per cent or less of the optimum rate of photosynthesis, 68 per cent were 10 per cent or less. Of the two cases in the highest class – 21-25 per cent – one was a measurement of low accuracy.

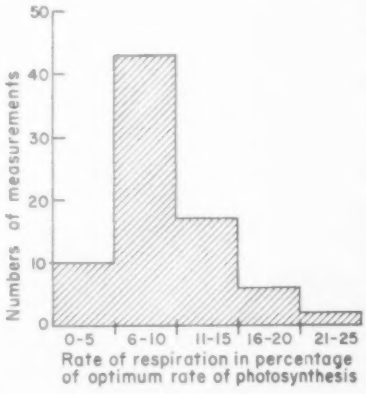

Fig. 10. The scattering of 78 measurements of respiration made during the *Dana* cruises 1956-1957.

As shown in the Section above, individual values may sometimes be susceptible to considerable experimental error. It is, beyond doubt, however, that the rate of respiration in percentage of light-saturated photosynthesis is always low. If in all cases the actual rate of respiration had been within the range of 6-12 per cent of light-saturated photosynthesis the variation of the measured rates due to the experimental error would not have been much different from that shown in Fig. 10. The relatively lowest percentages were found in typical shade plankton – on the average about 8 per cent.

According to the five *Galathea* curves showing photosynthesis as a function of light intensity (STEEMANN NIELSEN and JENSEN, 1957, Figs. 32-36) – the rate of respiration was 14 per cent of the light-saturated photosynthesis in the surface sample from the Tasman Sea and below 10 per cent in all surface samples from the tropical ocean. The respiration rates were also low in the seven series of experiments made during the *Galathea* Expedition but not specially described in the paper mentioned above.

During the two cruises of the *Dana* no area was found to show a particularly high relative rate of respiration. In the oligotrophic central area of the Davis

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Strait for example, the rates were not found to be especially high. If high respiratory rates are to be expected in oligotrophic water, then they should have been anticipated here in particular.

The individual measurements will be discussed in another paper (in preparation) where all of the data – primarily the curves showing the rates of photosynthesis as a function of light intensity – will be evaluated ecologically. It will be shown further in that paper that the method of presenting the rate of respiration in percentage of the optimum rate of photosynthesis is ecologically rather meaningless. This is particularly so when comparing the metabolism of typical " shade " plankton and " light " plankton.

(5) DISCUSSION

The idea of a respiration-rate nearly as high as the optimum rate of photosynthesis in the plankton algae found in unproductive waters was originally put forward by RYTHER (1954) as a means of explaining the discrepancy between the productivity measurements in the Sargasso Sea using either the oxygen technique or the carbon-14 technique.

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However, rate of respiration higher than 30 per cent of the optimum photosynthetic rate will, even in the upper half of the photic zone when integrated for all the algae found there, give rise to a decrease in the stock of algae, the rate of total respiration during 24 hours in that case being higher than the rate of total photosynthesis.

KETCHUM *et al.* (1958) have tried to estimate the rates of both net production and gross production throughout the year in the inshore and offshore waters of the Atlantic off New York. However, the methods employed hardly allow a direct comparison. In the offshore waters in March the rate of respiration should thus average 65 per cent of the optimum rate of photosynthesis, although all available data show the spring maximum in the offshore water to take place during this very month. Per 24 hours the respiration would be at least $1\frac{1}{2}$ times higher than photosynthesis even at the depth where the light conditions are most favourable. In the laboratory it is possible to create nutrient deficient cells showing a rate of respiration nearly as high as light-saturated photosynthesis. In nature, however, both grazing and sinking will normally prevent the continuance of a non-growing population. If 50 per cent of the cells are lost daily due to sinking and grazing – a very reasonable estimate – it takes only 3 days to reduce a non-growing population by a factor 10. Very extraordinary conditions must thus be found if a population of really deficient cells is to be created in nature.

Normally, when the nutrient conditions in the sea change from favourable to unfavourable, the old population of algae disappears in a relatively short time, and a population of algae species adapted to the scantier supply of nutrient salts takes its place. The size of the new population will remain much smaller than the old one. but the algae are by no means deficient in nitrogen and phosphorus. The size of a population seems primarily to be maintained by the balance between the zooplankton and the phytoplankton (cf. STEEMANN NIELSEN, 1958b).

In order to understand ecological conditions in a special habitat it is often pertinent to make a comparison with the conditions found in a somewhat different habitat. On land extremely unproductive areas are found. Often these are due simply to a

lack of nutrient salts. The northern-boreal and subarctic lichen heaths are a typical example. STÅLFELT (1938) made extensive investigations both of the rate of photosynthesis and of the rate of respiration in lichens. Table 1 gives, after STÅLFELT, the rate of respiration in percentage of the rate of photosynthesis at optimum light intensity at different temperatures in the lichen *Cetraria islandica*, a species typical of extremely oligotrophic localities.

Table 1. *Rates of respiration as a percentage of rates of photosynthesis at optimum light intensity in Centraria islandica from an oligotrophic habitat. Temperature inhibition of photosynthesis is found at* 25°C. (*After* STÅLFELT, 1938)

0°C	5°C	10°C	15°C
5·9	7·6	9·6	13·5

A lichen consists of both an autotrophic alga and a heterotrophic fungus. Therefore a rather high percentage might be expected, but this is by no means the case. On the contrary at temperatures normally found in the habitats of *Cetraria islandica* a really low percentage is found. If the respiration of the algal partner alone could have been measured an even lower percentage would undoubtedly have been observed. Thus, the rate of respiration is not at all high compared with the rate of photosynthesis in plant species in land habitats extremely poor in nutrient salts. The same phenomenon exists in the sea. Nature has created for every locality, if at all habitable, organisms which are specially fitted for it. One way is to develop species with adequate concentrations of enzymes for essential processes such as respiration and photosynthesis.

Finally this important question must be discussed : Is it necessary generally in productivity work to make measurements of respiration in addition to the measurements of photosynthesis ?

STEEMANN NIELSEN and JENSEN (1957) have shown how the variation of the percentage of the respiratory rate compared with the rate of photosynthesis influences the calculation of gross production when using the carbon-14 technique. If the rate of respiration is precisely 10 per cent of the rate of photosynthesis, the necessary correction to be introduced is + 10 per cent. If the percentage of respiration is 5 per cent or 25 per cent, the corrections to be introduced according to the article mentioned should be + 7 per cent and + 20 per cent, respectively. If the correction is made arbitrarily by adding 10 per cent the value obtained in the first case is about 3 per cent too high, and in the second about 8 per cent too low. The variation of the respiratory rate in a percentage of the maximum rate of photosynthesis seems to be found within the range 5-25, the highest percentage being found, however, only as a rare exception (Fig. 10). The influence of a respiratory rate differing from that arbitrarily chosen is thus insignificant if the rate of gross production only is wanted.

For the calculation of the net production per surface area per 24 hours the variation in the respiratory rate is more important. This part of the problem is treated separately in a subsequent paper by STEEMANN NIELSEN and HANSEN (in preparation).

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INSTRUMENTAL NOTE

Deep-sea cameras of the Lamont Observatory

(*Received* 19 *June* 1958)

INTRODUCTION

THE design of a wide-angle lens for underwater photography led to the construction of a series of underwater cameras during the period from 1949 to 1954 : a single-exposure camera, a multiple-exposure camera for 70 mm film and several multiple-exposure cameras for 35 mm film. Subsequently, two designs have been used with only minor changes on a dozen or more cameras. One has no shutter and is simple, compact, and rugged. Several thousand photographs of the ocean bottom have been taken with these cameras by a variety of operators – some with no previous experience. The second type has a shutter making them suitable for use in shallow water in daylight but also less simple to make and service. They have received little use and will not be described here.

This article is limited to the description of the equipment now in use by the Lamont Geological Observatory and makes no attempt to review the field of deep-sea photography (See : EWING, *et al.* 1946 ; EDGERTON and HOADLEY, 1955 ; LAUGHTON, 1957 ; SHIPEK, 1957).

OPTICAL SYSTEM

The standard optical system consists of a Leitz Summaron lens having a focal length of 35 mm and a relative aperture of f/3·5 close behind a plane glass window 1¼in. thick. The lens, as manufactured for the Leica camera, is supplied in a focusing mount. This mount is removed and discarded. The lens can then fit in a 1¼ in. diameter hole in the camera case. The small hole and thick window provide the strength needed for work on the ocean floor. A picture size of 1½ in. × 1½ in. is obtained on unperforated 35 mm film. This gives an angular field of view in water of 42° × 36°. Chromatic aberration resulting from the passage of light from water into air makes the corners of the photographs somewhat fuzzy. This defect can be overcome by using a correcting lens (THORNDIKE, 1955) in water in front of the camera window. As one of the glasses used in the correcting lens is attacked by sea-water, the lens must be cleaned in fresh water and protected from salt spray when not in use. Even with these precautions, the lens must have the surface repolished and the elements recemented occasionally. For these reasons, the cameras are often used without correcting lenses.

An alternative optical system employs a wide-angle lens designed for operation in water (THORNDIKE, 1950). The lens has a paraxial focal length of 28·2 mm, a relative aperture of f/11, and an angular field of 75°, all in water. The diameter of the picture is 1½ in. If a camera is to be used in water containing considerable suspended matter so that the camera must be close to the object being photographed and hence a wide field of view is required, this optical system is superior to the standard one, but the lens is slower and has considerable distortion. In addition, the complete lens is not available commercially so the individual elements must be mounted and adjusted.

FILM TRANSPORT MECHANISM

Normally the camera is loaded with 20ft. or less of unperforated bulk film wound on the unexposed-film spool, but a commercial film cassette can be substituted for the spool. An electric motor moves the film slightly more than 1½ in. after each exposure. The time for transport can be adjusted from a few seconds to several hours by the choice of motor speed and gears between the motor and the film spool. Times of approximately 30 seconds have been found satisfactory for bottom photography (Figs. 1 and 2).

STARTING SWITCH

The starting switch which has been used most (Fig. 3) was designed about ten years ago by

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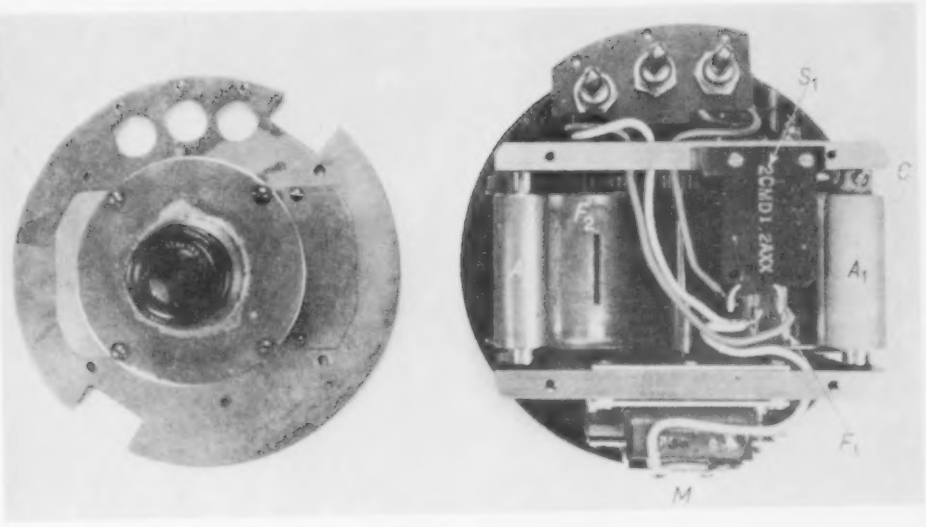

Fig. 1 (a).

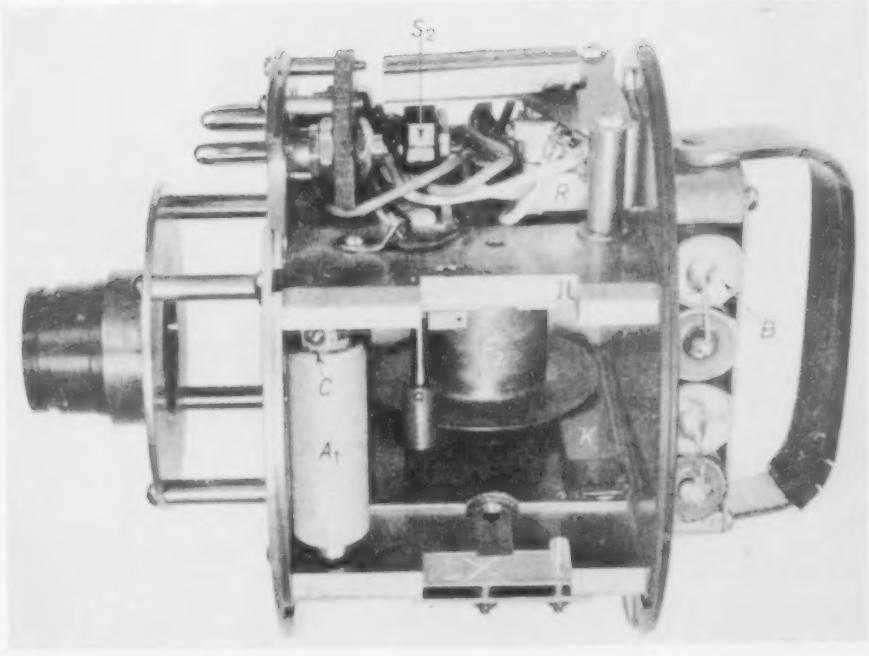

Fig. 1 (b).

Fig. 1 (a, b). Camera mechanism. The film passes from the unexposed-film spool, *F*1, over the rubber-covered roller, *A*1, over a polished plate, over a brass roller, *A*2, and onto the exposed-film spool, *F*2. A Brailsford motor, *M*, is geared to the spool *F*2. A brake, *K*, presses against the spool, *F*1, to keep the film under tension. The switch, *S*1, is actuated by a cam, *C*, mounted on the end of *A*1. The switch, *S*2, is actuated by an external magnet.

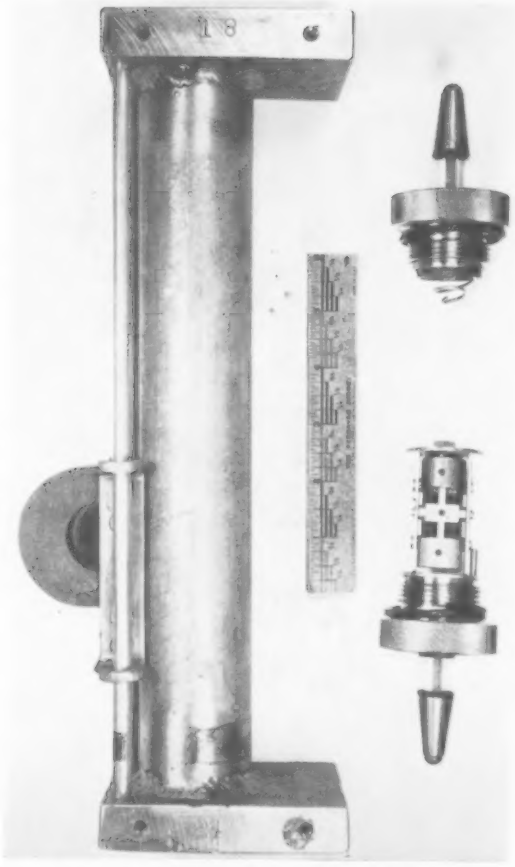

Fig. 3. Starting switch and housing. The stainless steel tube at the left of the photograph contains four size-D flashlight cells. It is threaded at the ends to receive the plugs shown on the right. The lower plug has a microswitch mounted behind a lever which is pivoted at the centre and has brass and iron weights at opposite ends. When the magnet mounted on the tube slides down, the lever is unbalanced and the switch is activated.

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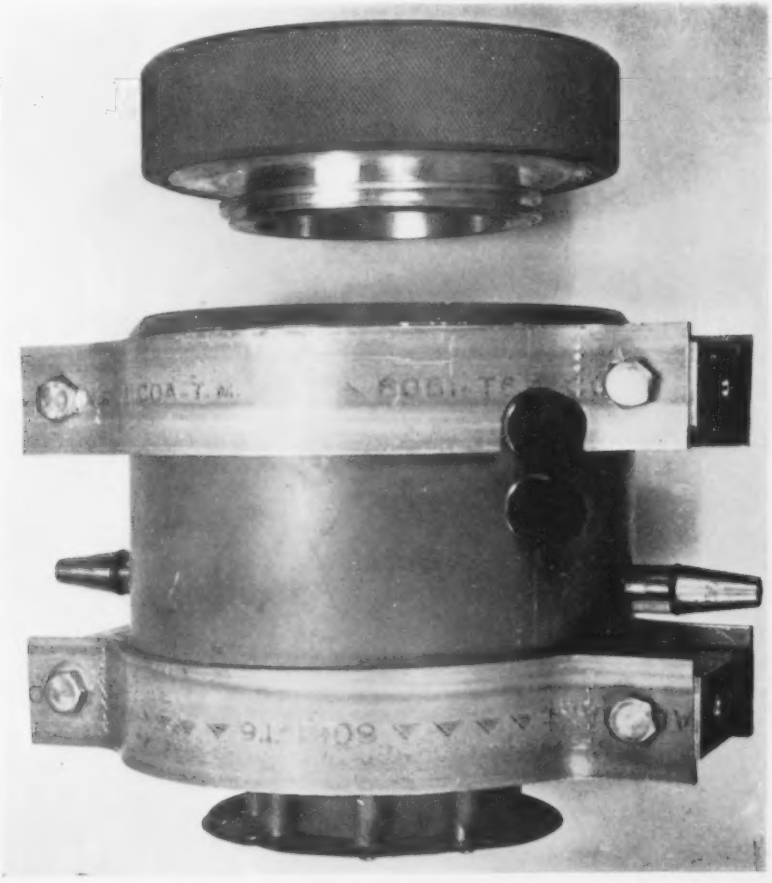

Fig. 5. Camera housing made from 7 in. diameter aluminium bar. Inside diameter is 4¼ in. The end cap is threaded into the tube with very loose rectangular threads and sealed to it with an " O " ring. The window is held on with a light, flexible monel clamp and sealed with an " O " ring. Electrical connexions are brought through the wall with insulated bushings sealed with " O " rings.

Fig. 6. Complete deep-sea camera.

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J. L. Worzel for use with a single-exposure camera. A second type of switch, which has received much less use, employs a special splatterproof mercury switch which closes the circuit when it is

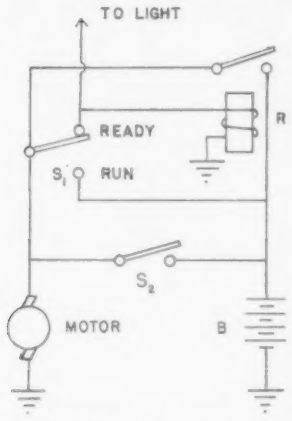

Fig. 2. Camera wiring. The cycle of events is as follows. The switch, S2, is closed by whatever device is used to indicate that a photograph is to be taken. (In photography of the ocean floor, a trigger weight strikes the bottom causing a magnet to move near to an iron armature and attract it thus actuating the switch). Current now flows through the relay, R, causing it to close, through the relay in the light source causing the light to flash, and through the motor causing the film to start transporting. After the film has moved a short distance, the switch, S1, is snapped from the " ready " to the " run " position and the relays open. The operator causes S2 to open by raising the camera off bottom. When the film has transported slightly more than 1½in., one revolution of the rubber-covered roller, the switch, S1, is snapped to the " ready " position by the cam and the camera is ready for the next picture.

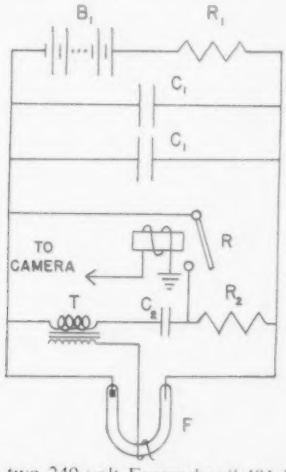

Fig. 4. Light wiring. Battery, B_1, two 240-volt Eveready # 491 in series ; condenser, C_1, Sprague FF1, 525 μF ; condenser, C_2, Cornell-Dublier # TWC 10P1, 0·1 μF ; flash tube, F, General Electric, FT-118 ; ionizing transformer, T, Heiland # 65H-19 ; relay, R, Price # 1001-C, 120 ohms ; resistance, R_1, 6,000 ohms ; resistance, R_2, 2 megohms. (In earlier work, the high potential was obtained by the use of a circuit suggested by H. E. Edgerton employing a 4-volt storage battery, a vibrator, a transformer, and a selenium rectifier. The condensers, C_1, were connected in series and FT-110 or FT-218 tubes were used).

inverted. Both of these arrangements require a separate housing for the switch. Considerable simplification has been effected in a new arrangement in which a microswitch (S2 in Fig. 1b) is mounted on the camera itself with a stiff phosphor bronze spring pressing against it to hold it in the open

position. Two rods of soft iron are threaded through the wall of the aluminium housing containing the camera and sealed to it with soft iron caps and " O " rings. The inner ends of the rods are close to a soft iron armature attached to the phosphor bronze spring. When a magnet is moved near to the outer ends of the iron rods, the armature is attracted and the microswitch closed.

LIGHT SOURCE

Illumination for the photographs is obtained by discharging two 525 μF electrolytic condensers, each charged to approximately 450 volts, through an electronic flash tube (Fig. 4). (Larger units have been constructed for special purposes, but this is the standard arrangement). The flash is of such short duration that motion of the camera or of the film does not impair the image.

A variety of reflectors have been used to confine the light to the region being photographed and to produce as uniform illumination as possible. Obviously, the type of reflector depends upon the geometrical arrangement of the light, camera, and area being photographed so that no one reflector will be ideal for all cases. A reflector to give reasonably uniform illumination for front lighting has been designed and spun from copper which was subsequently nickel-plated. However, in most work side lighting has been desired to show the texture of the bottom. With this geometry, any slight tipping of the frame which, of course, changes the direction of the light relative to the bottom, effects the illumination drastically, and it is next to impossible to design a reflector which will consistently give uniform illumination. As a result, simplicity of construction has been the determining factor and straight-walled stainless steel mixing bowls have been used.

SIGNALLING SYSTEM

In order to work at all efficiently in deep water, some means of informing the winch operator that the camera has struck bottom is essential and a device which, in addition, shows whether or not the camera is operating properly, is highly desirable. Two methods have been used to accomplish these ends. In the first, the cable which supports the camera contains an insulated wire, the lower end of which is connected to the camera motor and the upper end to a voltmeter. The main cable serves to complete the circuit. In principle, this arrangement is almost ideal, and it has been used with success, but it requires a special cable and, in practice, there have been difficulties from kinks and breaks in the insulation on the wire, so it is not being used at the present time. The second method relies upon a sound source to send a signal from the camera to the ship. A convenient arrangement is to have the frequency of the source the same as that used on the ship's fathometer, so that the latter can be used as the receiver. Magnetostriction and ceramic transducers driven by a variety of circuits have been used. An arrangement, which was particularly successful, employed a ceramic transducer made by the Edo Corporation, driven at 12 kc/s for two brief periods each two seconds, so that the operator heard a characteristic " peep-peep " as the camera descended. On striking the bottom, the signal was shut off warning the operator to stop lowering the equipment. The details of construction will not be given here as changes are currently being made in an attempt to obtain smaller weight and greater range. It is difficult to give quantitative information on the performance of the devices used as reports from different observers vary widely. However, the equipment has worked well down to 2,000 fathoms and more.

HOUSINGS

Three materials have been used in making housings for the deep-sea cameras described above : aluminium, forged K-Monel and cast H-Monel. (In addition housings for starting-switches have been made of stainless steel and brass and one large light source has a steel housing). A set of forged K-Monel housings given by the International Nickel Company proved very satisfactory from the point of view of strength and resistance to corrosion. However, the high cost of monel and of machining it have made it seem unwise to adopt this material for standard equipment. Cast H-Monel end caps impregnated with a plastic by the American Metaseal Corporation proved entirely satisfactory, but no complete housings have been made in this way. Aluminium has been used in most housings. It is readily available, light, strong, relatively inexpensive, and easy to machine. When painted or coated with grease, it has not been subject to excessive damage from corrosion. Housings are pressure-tested at 10,000 p.s.i. and will probably withstand considerably higher pressures.

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Acknowledgements—During the development of these cameras, valuable suggestions were received from many members of the Observatory staff, particularly from those who operated the cameras or who participated in their construction. The cameras are, therefore, the product of the group rather than of any individual.

Lamont Geological Observatory, Columbia University, Palisades, New York.
Lamont Geological Observatory Contribution No. 320 *supported by the Navy Department, Contracts NObsr* – 39092, 43355, 64547 *and Nonr* 266 (48).

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LETTER TO THE EDITORS

A remarkable leptocephalus from off the coast of Washington

(*Received* 1 *May*, 1958)

THE specimen herein reported upon is part of a collection of bathypelagic fishes from off the coast of Washington which came to the author through the good offices of Dr. Norman J. Wilimovsky of the U.S. Fish and Wildlife Service. This specimen seems noteworthy because of its size and shape and because there is apparently no record of anything resembling it in the literature.

Collection data : " John N. Cobb," Drag. No. 44, June 13, 1956, 47° 56·5′ N., 125° 55·4′ W., depth of trawl 15-16·5 fathoms, bottom depth 850-950 fathoms, started dragging at 0142.

Description : Total length approximately 278 mm, greatest body depth about 115 mm, distance from snout to apparent origin of dorsal fin fold 74 mm, snout to vent length about 144 mm, head length 11·5 mm, depth of head behind eye 8·0 mm, horizontal diameter of eye 2·8 mm, snout 4·5 mm, interorbital 1·7 mm, caudal rays 6, dorsal rays more than 116, anal rays more than 70, myomeres about 155 (correct number not shown in the figure).

The specimen is an extremely deep-bodied leptocephalus of relatively great total length. The myomeres are more widely-spaced in the centre of the body than at either extremity. The septa do not run to the edges of the body but stop short, forming a border of from one to six millimetres in width around the margin of the fish. The convoluted and relatively thick-walled gut runs in the border on the anterior half of the ventral margin of the fish, and an organ presumed to be the liver is also present in this area a short distance behind the head. The vertical fins are frayed, and their exact extent is difficult to determine. Both the dorsal and the anal fin folds probably extend further forward than the figure indicates. Fin rays have formed in the posterior portions of the fin folds but are still absent anteriorly. A separate caudal fin is apparently present, but this may be an artifact. The pectoral fin is placed slightly behind the gill opening and has a base that is shorter than the gill opening and which is almost at right angles with the horizontal. The pectoral fin rays are just beginning to appear in the membrane. The gill membranes are broadly joined and attached to the isthmus thereby greatly restricting the gill opening, which extends upwards to the level of the lower margin of the orbit. The head is strongly compressed, and the interorbital is convex and narrow. The small eyes project rather markedly from the head, but they are not tubular. Both of the nostrils lack tubes. The larger, posterior nostril is an elongate slit at the antero-dorsal corner of the eye, while the anterior nostril is a smaller opening located about midway between the top of the snout and the anterior margin of the orbit. The narrow, beak-like jaws each contain a single row of small, needle-point teeth. A gap is present between the anterior-most tooth of the upper jaw and the other teeth in the upper jaw series. There are apparently no other teeth. The body of the fish in alcohol is light tan ; the gut and head are slightly darker. There are no large chromatophores.

Possible identity : This leptocephalus differs from almost every other known leptocephalus in its great body depth. Some exceptions are *Leptocephalus latissimus*, *Leptocephalus pseudo-latissimus* (BERTIN, 1938) and the leptocephalus of *Cyema atrum* (ROULE and BERTIN, 1929). The present specimen differs markedly from *C. atrum* in being larger, having more myomeres, lacking pigment spots, having less elongate jaws, having the eye more centrally placed on the head, and in various other ways as well. It differs from the former two species (referred to the Lyomeri by BERTIN, 1938) primarily in having a much different jaw structure and a much longer body, although there are other differences as well.

Three eels known from Bering Sea or the north-eastern waters of the Pacific are *Synaphobranchus bathybius*, *Nemichthys scolopaceus* and *Avocettina gilli*. Although synaphobranchid eels are known to have large leptocephali with high myomere counts (BRUUN, 1937) they are invariably elongate, narrow-bodied forms. The leptocephalus of *N. scolopaceous* is likewise an attenuate animal (ROULE

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and BERTIN, 1929). The leptocephalus of *A. gilli* is apparently unknown ; however, it seems logical to assume that in forms as similar in the adult stages as are *Nemichthys scolopaceous* and *Avocettina gilli* the leptocephali would also show similarities.

Along the California coast we find the eel families Nettastomidae, Congridae, Ophichthidae and Muraenidae. Leptocephali of Mediterranean species of these families are all elongate forms (D'ANCONA, 1931). In addition a species of *Serrivomer*, another nemichthyid is found, and this genus also has an elongate leptocephalus (BEEBE, 1936).

The leptocephali of most eel species are as yet unknown. Thus we may not draw too sweeping a conclusion from the above generalities. It seems safe to say, however, that our leptocephalus represents a species of eel hitherto unknown in the north-eastern Pacific. Although this leptocephalus cannot contend, in the matter of size, with the giants captured by Danish expeditions (BERTIN, 1954) it further serves to point out the paucity of knowledge on the identity and life histories of many oceanic organisms.

I am endebted to Miss Esther Coogle for her care in preparing the figures.

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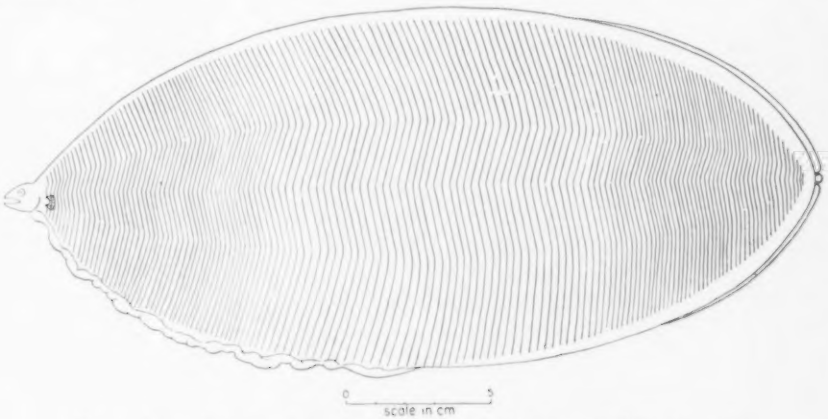

Fig. 1. Lateral view of a leptocephalus taken off the coast of Washington.

Fig. 2. Enlarged view of head of leptocephalus taken off the coast of Washington.

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BOOK REVIEWS

J. J. STOKER : **Water Waves.** Interscience New York, 1957. 567 pp., 88s.

SINCE the announcement of its forthcoming publication, Professor STOKER's book has been eagerly awaited by those with interests in pure and applied hydrodynamics. Now that *Water Waves* is available, it is indeed seen to be a book of the highest quality.

Before mentioning its merits it might be as well to say that those who seek a comprehensive account of the behaviour of waves in the ocean may be disappointed not to find a discussion of ideas concerning the generation of waves by wind, growth of the wave spectrum and the role of turbulence. These are at the present time with few exceptions either empirical and concerned only in part with hydrodynamics or theoretical and incapable of explaining the facts (cf. URSELL, 1956). Professor STOKER has concentrated on the mathematical theory of waves on the surface of an incompressible non-viscous fluid. Precise answers to many problems are available and he is at pains to show whenever possible the link between his results and those of oceanographers and meteorologists and gives many references.

The theory is in large part the result of recent research, the older work being introduced as necessary to give continuity to the development. The author says that the book is rather personal in character and indeed a considerable part is devoted to his own researches and those of his colleagues. That we are presented with a systematic treatment of many aspects of wave motion is a tribute to the comprehensiveness of the work at New York University and must make the book one of the most authoritative written on water waves.

The first chapters introduce the two pertubation methods which form the basis for the remainder of the book. One leads to the linearised small amplitude theory of surface waves and the other to a non-linear shallow water theory based on the hydrostatic relation.

The linear theory occupies nearly half the book and a full account is given of the recent theories of waves approaching a sloping beach. In this connexion there is a reference to, but no discussion of, edge waves which are now thought to be of significance in certain oceanographic situations. The other work discussed at length is the author's joint theory with Peters of the motion of a ship in a sea-way – a rigorous development of a linearized system of equations applicable to a wide variety of hull shapes but which are probably very difficult to apply in practical problems. In addition many other well known classical solutions (e.g. Cauchy–Poisson waves from a source) are investigated and new light is shed on them.

The shallow water theory is non-linear and there is an analogy with compressible flow in gas dynamics for which the extensive theory of characteristics has been developed. This theory is carried over to water waves and is used to discuss the breaking of waves, formation of bores, a number of problems in hydraulics and a simplified model of the formation of atmospheric fronts.

In the closing chapter there is an exposition of Levi–Civita's theory of waves of finite amplitude. As far as the reviewer knows this is the first time that the theory has been included in an English language book on waves.

It remains for me to say that a real merit of the book is the delightful manner in which the author has combined his formal mathematical arguments with a most informal and readable descriptive style – a rare quality indeed.

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Proceedings of the U.N.E.S.C.O. Symposium on Physical Oceanography : Tokyo 1955. Published jointly by U.N.E.S.C.O. and the Japanese Society for the Promotion of Science, 1957. 292 pp. $4.50, 22*s* 6*d*, 1.350 francs (Fr.).

OCEANOGRAPHERS will know about the Marine Science Programme of U.N.E.S.C.O. which was set up in 1955 with the establishment of the International Advisory Committee on Marine Sciences (I.A.C.O.M.S.). The present publication presents the fruits of a meeting staged in Tokyo from 19 to 22 October 1955 under the aegis of U.N.E.S.C.O.'s pre-existing Interim Advisory Committee on Marine Sciences which had been established in 1954. Because U.N.E.S.C.O.'s interest in Oceanography stems very largely from Japanese stimulation, the venue of the meeting was well chosen.

The symposium was attended by about 100 Japanese delegates and observers and also by participants coming from seven other countries and from international organizations. The forty-six papers printed in the book under notice are all in English despite the great numerical dominance of Japanese authors. Eleven of them belong to a session on Instrumentation ; twenty to one on Circulation ; and fifteen to the third session which was on Information. That the Tokyo meeting, which followed upon both a regional gathering of representatives of Marine laboratories and the sixth session of the Indo-Pacific Fisheries Council will stand as a red-letter occasion in the U.N.E.S.C.O. programme for aiding marine research, will be abundantly clear to all who see this report.

Bulky publications which present the numerous papers delivered at symposia are not rare these days, and Oceanography has its share of them. Two faults can be found with such welcome volumes. The first is that they are very difficult indeed to review ; the second is that they present something of a nightmare problem to the assiduous bibliographer who wants always to have cards in his index affording an author, subject and regional coverage of all noteworthy literature appertaining to his subject. The great labour which inescapably goes to the production of such large and informative publications as that under notice, would be little increased if the Contents List were printed in block form in a special way. Without exceeding the width of a common index card, the various items in the Contents List could be well spaced vertically, and below each could appear in very small print a common but adequate specification of the volume. Such provision would be a boon to librarians who could then have the list photostatted to provide " cut-ups " for sticking on to cards for author, subject, region, etc. It would be better still if extra copies of the Contents List could be provided. The suggestion is very seriously made here.

The session on Instrumentation was chaired by Dr. G. BÖHNECKE, President of the German Hydrographic Institute who contributes a 3 page paper on methods of investigating oceanic circulation. Dr. G. E. R. DEACON followed with a brief description of the Swallow Neutral Buoyancy Float which has been used so successfully to track deep ocean currents. He was able to cite only the early results obtained by the use of it. K. TERADA reports upon Japanese devices which convert mechanical deformations into electrical signals, and writes of the adaptation of them to wave measurement. There followed two brief papers which presented some account of a couple of new Japanese current meters. Though of praiseworthy ingenuity the reviewer sees in them no attempt to overcome the difficulties attendant upon ship motion. A following paper describes NAN'NITI's phototube current meter and also the other modern Japanese instrument known as the T.S. Current Meter. ISHIGURO's floating self-recording wave-height recorder is described by M. NAKANO who also writes about the ISHIGURO and WATANABE wave-pressure recorders in a paper which deals as well with TSUKAMOTO's telemetering tide-gauge, AGARI's remote-reading thermometer, NAN'NITI's plastic water sampler, and the last-named's improvement of the Forel Colour Scale.

There is a paper by KUSUNOKI on a method of sampling sea ice and one by three other Japanese authors on a microanalytical method of determining chlorinity. This latter affords a great saving of reagents and is claimed to involve no material diminution of accuracy. The same three authors describe also an automatic potentiometric titrator. Comment was made from the floor that temperature would have to be measured with high accuracy and care. T. SASAKI describes three new Japanese instruments – one a thermograph which affords a temperature profile down to 200 m depth ; one an underwater camera, and the other a towed electrodes assembly for measuring currents from a ship under way. A. C. VINE of Woods Hole contributes a paper in which he discusses the features of the latest precision echo-sounders ; describes briefly the new electrical conductivity methods for determining salinity ; remarks upon the use of buoyant floats (to replace cables) which can reside a while on the sea floor and then return to surface ; comments upon the anchoring of buoys in great depths of the open sea ; discourses upon the use of surface floats for making current measurements ;

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describes model studies of ocean circulation ; gives a few comments on the radio-telemetering of oceanographic data, and states what he considers should be the main features of a modern research vessel.

There follows a paper by INOUE and two associates on the perfection of a turbidity meter ; on the direct photography of suspended matter in the sea, and on an observation chamber (a sort of cable-hung bathysphere) in which two or three observers may go down to 200 m depth for from 3 to 5 hr. There is a discussion of " marine snow " and pictures are given of the chamber named " KUROSHIO-GO." In this paper there is an impressive transparency profile for a position in the North Pacific.

The INOUE paper is followed by a very impressive one by J. JOSEPH of Hamburg who is renowned for his studies of transparency through the measurement (horizontally) of extinction coefficient from a moving ship. JOSEPH details his optical way of revealing the concentration of suspended matter at thermoclines and dwells upon the importance of the information with regard to sound scattering, false bottoms, and to the movement of water bodies – the latter having its bearing upon sand transport. He deals with time changes in the vertical distribution of turbidity and presents his remarkable diagrams which show that in the Kattegat (in 1949), a vertical section displaying extinction coefficient values for ultra-violet light had extraordinary resemblance to one portraying the density distribution at the same time in the same section. We see again JOSEPH's sections North-South and East-West running through the central point of the North Sea in August 1953 which show how remarkably the turbidity revealed the pronounced thermocline of which DIETRICH has elsewhere given a temperature plot. JOSEPH's diagrams are of great interest relating also as they do to the sea east of southern Greenland and to the entire Irminger Sea – the latter in respect of surface turbidity. We see a turbidity portrayal of the water tongue stretching north-eastwards across the Flemish Bight of the North Sea and are given a correlation for that region between extinction and plankton abundance. This is a very fine paper and its delivery in Tokyo must have been most welcome as a fitting conclusion to the session on Instrumentation. It is especially welcome to have so much of JOSEPH's work brought together and presented in English in a single paper.

Quite clearly a reviewer cannot aim to present here any worthwhile scan of the twenty papers on Circulation which follow. If passing attention only is given to the 16 papers on very varied topics which involve twenty Japanese authors (because they are " home papers " to so speak), it is hoped that no discourtesy will be seen in such action nor any intended assessment of relative value read into it.

As regards the north western Pacific Ocean the volume includes papers which deal with the variation in oceanic conditions ; on forecasting surface temperature, and on areas of divergence and convergence of surface currents. Coastal upwelling off the Californian coast with its effects on productivity is discussed ; wind-produced vertical circulation is considered in relation to submarine geology and topography ; research on circulation fluctuations is written about ; and variations of oceanic circulation are dealt with. Variations in the Kuro Shio in relation to changing daily sea-levels are the subject of one paper ; the convective circulation is that of another ; the dynamics of the Kuro Shio off southern Japan are discussed in yet another – whilst HIDAKA devotes his paper in the session to the circulation of the Pacific Ocean as a whole. There is a Japanese paper on the deep circulation in the north-western Pacific with reference to the vertical distribution of oxygen ; this paper is followed by one concerned with the oxygen distribution alone. The distribution of some minor bio-elements in western Pacific waters and the quantitative distribution of chemical elements in sea-water are the subject of the last two of the Japanese papers in the session on circulation.

Of the four papers by visitors the first is by DEACON (who chaired the session) on the deep-water circulation of the Pacific Ocean. Starting from the opinion that the most important thing to understand better is the mechanism whereby the accumulated nutrients of the abyss are lifted up into the photic zone, he called for more high-quality observations in the great depths and on the bottom of the temperature and salinity situation. Thereby the vertical circulation will become better understood.

The second of the two papers delivered by visitors to Tokyo is by ROCHFORD of Australia, amongst whose special studies, those on coastal and estuarine water conditions are so well known. His contribution is on " The use of water mass composition in the interpretation of eastern Australian coastal oceanographical data." ROCHFORD deals with the circulation of the Tasman Sea and gives diagrams depicting the seasonal distribution of the principal surface water masses between Sydney and Wellington. He derives their probable paths of movement and goes on to discuss oceano-

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graphical trends in the ocean off eastern Australia. A feature worthy of note is the amount of work ROCHFORD has contrived to do without the possession of facilities for regular work from a specialist modern research vessel ; simple equipment used from liners and motor boats provided the bulk of his data.

The third " visitor's paper " was by F. DE BUEN ; it discusses the pelagic fishes and the oceanographical conditions along the northern and central coast of Chile.

The fourth paper by a visiting scientist was given by DR. ANTON BRUUN of Copenhagen on " The Ecological Zonation of the Deep Sea." His great experience in round-the-World oceanographical research gained from the " *Dana* " and the " *Galathea* " expeditions invests such a paper as that now under notice with special importance. BRUUN gives a chartlet of the Atlantic wherein is portrayed (with myomere counts) the distribution of the Leptocephali of the North Atlantic freshwater eel, the conger eel, and the deep-sea eels. In an interesting diagram he plots the catches of freshwater eels in western Europe and in Denmark against SMED's surface salinity anomaly data relating to the North Atlantic with the eel-catch curves shifted 10 years onwards. He sees striking-enough parallelism between the three curves to think that a similar thing should be done with other fish yields. BRUUN finishes his paper with a discussion of the distribution of the mesopelagic decapod cephalopod Spirula spirula which the reviewer mentions here because BRUUN gives a World chartle wherein he plots the distribution of the animal against certain temperature isolines for the surface and for 400 m depth.

The session on information was chaired by Dr. R. REVELLE and the papers are by Indian, Thai, Vietnamese, Chinese, Japanese and Russian contributors. Half of them are devoted to making known the state of oceanography in the various countries, but the Chinese paper deals with the study of reef corals as evidence of palaeotectonics. Six Russian papers cover a wide spread of topics:– floor relief, bottom deposits, and bottom fauna in the north-west Pacific ; the regularities of plankton distribution there ; certain chemical features of the waters and sediments there ; and, in general, oceanographical research conducted by the U.S.S.R. there.

We pick out for special measure of attention the striking 4½-page paper by N. N. SYSOIEV entitled : " Developments and Future in the Oceanographic Instrument Construction in the U.S.S.R."

Many readers of Deep-Sea Research will, like the reviewer, find much impressive information in this paper which deals with instrumentation and methods progress in oceanography made during the last ten years by the Russians. We read something of their latest echo-sounders ; of their high-fidelity photometers ; of their bathythermograph ; of their various methods of measuring currents from both stationary and moving ships, and of their automatic radio buoys adapted to signalling floe-drifts.

The Soviet instrument for registering the travel of a trawl over the sea-floor is referred to and readers can quite readily agree with the value claimed for such a device when " numerical countings " of bottom fauna are intended. The implement is not, however, completely novel ; " bottom walkers " have been earlier used in such devices as epibenthic dredges.

SYSOIEV writes about Soviet underwater television apparatus used down to 500 m depth and about submarine cameras employed beneath 3000 m of water.

Especially heavy anchors and trawls have allowed the Russians to anchor and trawl at all depths. For the future (we read) special attention will be given to the development of methods permitting the rapid collation of all sorts of data whilst the research vessels are at sea ; to intensifying observing at very great depths, and to the elaboration of automatic devices which can be left to work by themselves for lengthy periods.

The paper makes it known that the Russians are busy with electrical conductivity methods for determining salinity – as also with the simple method which involves weighing a submerged quartz float on an accurate torsion balance. This latter method is of course, much in use in Germany already by K. KALLE. SYSOIEV writes of the Russian towed electrodes assembly for measuring ocean currents from a cruising ship and claims that advances on the American G.E.K. are made by the Soviet's " EMIT." There is also a good deal about instruments applied to wave-measuring, but what many readers will find of particular interest are the remarks made about the winch equipments on the large new Soviet research vessels. The *Vitiaz* possesses what is referred to as an ingenious (" ingenuous " in the Tokyo-printed paper under review) arrangement whereby deep sea cables are not stowed under high tension on the powered drum which heaves them in. This of course, is the main feature of the Swedish *Albatross* Expedition's winch later used aboard *Galathea* and now in

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the U.S.A. where another of the kind also exists. On the *Vitiaz* the hauling tension of 20 tons is dropped to 0·2 tons at the storage drum. The anchor winch carries 13·6 km of cable which tapers in diameter from 25 to 15 mm, whilst the main trawling winch carries 15·4 km of the same thinning from 15 to 8·5 mm in diameter.

Using her fine winches, the *Vitiaz* has occupied 150 anchor stations in depths down to 5000 m and has performed more than 200 deep-water trawlings of which some have been below more than 9000 m of water.

J. N. CARRUTHERS

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NEWS AND NOTES

Communication concerning a Central Agency for ^{14}C determination (Measurements of primary production in the sea) at Charlottenlund Slot, Denmark

DURING recent years the study of the primary production in the sea has been one of the main concerns of marine science. The present great interest in productivity is due inter alia to the use of the radioactive tracer ^{14}C as a tool for measuring primary production in the sea regardless of the size of the production. Steemann Nielsen first employed the ^{14}C-method for measuring the production of organic matter in the sea on the deep-sea expedition of the "*Galathea*" 1950-52. The technique has now been used by many investigators all over the world, and it has been routinely included in oceanographic data gathering voyages and on light ships, where the field work is made by the crew.

The most recent description of the different modifications of the ^{14}C-method is found in the articles B.2 and B.3 in "Contributions to Plankton Symposium 1957, Measurements of Primary Production in the Sea." Rapp. et Procès-Verbaux des Réunions (Cons. Perm. Intern. p. l'Explor. de la Mer), Vol. 144, 1958.

An important factor in the usefulness of the ^{14}C-technique for measuring primary production is that the field work does not presuppose any expert knowledge. On the other hand, the manufacturing of the ampoules containing the solution of $NaH^{14}CO_3$ to be used for the experiments requires a well equipped laboratory and a scientist familiar with radioactive tracer work. The same is true concerning the measurements of the radioactivity of the filters containing the samples.

Whereas large oceanographic institutions ordinarily will have such an expert at their disposal this will not be true for many other marine laboratories. In several instances therefore various institutions have co-operated. The ampoules to be used have been manufactured at one place and sent to another where they have been used for productivity work. The dried filters with the radioactive plankton have in turn been sent back to the first place for measurement. As the half life of ^{14}C is more than 5,000 years, the filters, if properly stored, remain unaltered for a very long time.

During the symposium on "Measurements of Primary Production in the Sea" held at Bergen 27th–29th September 1957 by the International Council for the Exploration of the Sea, an *ad hoc* working committee was appointed to deal with the methods for the measurement of primary production. The members were : John H. Ryther (chairman), Grim Berge, Maxwell S. Doty, G. E. Fogg, and E. Steemann Nielsen.

The committee presented recommendations which were adopted unanimously by about 80 participants of the symposium. One of the paragraphs read : It is suggested that a central agency be established, for example at Charlottenlund under the direction of Prof. E. Steemann Nielsen, which would provide standardized ampoules of ^{14}C, counting of ^{14}C samples, and calculation of carbon assimilation rates."

In January 1958 Unesco provided funds for establishing the Agency. The "Danish Institute for Fisheries and Marine Research" provided a room at its residence at Charlottenlund Castle, Denmark.

The Agency is organized on a non-profit basis. Professor E. Steemann Nielsen, who is adviser on plankton research to the "Danish Institute for Fisheries and Marine Research," will be honorary supervisor. The daily work will be directed by Mr. Vagn Hansen of the same institute. The facilities of the Agency, which was officially opened during the meeting in October 1958 of I.C.E.S. (The International Council for the Exploration of the Sea), are available to all scientific institutions in the world. The consignments will be made in accordance with rules set up by the Danish Ministry of Health.

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Standardized ampoules of ^{14}C-activity 0·004 mc – may be obtained from the Agency at the following prices :

100 ampoules or more	D.Kr. 2·75 each
50-99 ampoules	D.Kr. 3·00 each
less than 50 ampoules	D.Kr. 3·25 each

If the purchaser wishes to have the filters containing the samples from experiments counted by the Agency the total price (including ampoules and numbered membrane filters) will be :

100 ampoules or more	D.Kr. 5·00 each
50-99 ampoules	D.Kr. 5·25 each
less than 50 ampoules	D.Kr. 5·50 each

The prices include packing, but exclude transport. Special boxes for the return of the filters when the counting is to be done by the Central Agency will be provided.

The salinity of the sea-water used for the experiments must be stated by a customer. It will be sufficient for water from the open ocean to be designated " ocean water." The photosynthetic rate will be computed by the Agency. When using either brackish water or freshwater it will be necessary for the customer to determine the total concentration of carbon dioxide in the water.

The water samples to be used for the experiments should be taken with a glass, plastic, or other type non-metallic, non toxic sampler.

Directions for use of ^{14}C tracer will be enclosed in each consignment.

A filtration apparatus operating by pressure obtained by a bicycle pump may be provided from the Central Agency at a price of D.Kr. 300·00.

A suitable water sampler may be provided by Laboratoire Hydrographique, Copenhagen, at a price of 830·00 D.Kr.

Field kits for sample collecting, filtration apparatus, filters, etc. may also be provided, on request and at cost price, by Prof. Maxwell S. Doty, Botany Department, University of Hawaii and by Dr. John H. Ryther, Woods Hole Oceanographic Institution, Woods Hole, Mass., U.S.A.

Special holders to be used when drying filters may be obtained at a price of D.Kr. 8·00 each.

Denmarks Farmaceutiske Højskole
Botaniskdl, Afdeling
Universitetsparken 2
København, Denmark

E. STEEMANN NIELSEN

Publications issued by the International Association of Physical Oceanography

The Association issues two series of publications, viz. " Publications Scientifiques," at irregular intervals, and " Procès-Verbaux."

The following numbers have appeared. Prices are given in brackets ; * indicates out of print. Publications Scientifiques.

No. 1. S.F. GRACE :

I. Historical review of dynamical explanations of tides in non-elongated enclosed seas and lakes.

II. Historical review of dynamical explanations of the tides of the Mediterranean, the Baltic Sea, the Gulf of Mexico, and the Arctic Ocean. (1931).*

No. 2. Tidal Bibliography (Third instalment). (1932).*

No. 3. Bibliography on tides and certain kindred matters (Fourth instalment). (1936). (1s.)

No. 4. PHIL E. CHURCH : Temperatures of the Western North Atlantic from thermograph records. (1937). (1s. 6d.)

No. 5. Monthly and annual mean heights of sea-level, up to and including the year 1936. (1940). (22s.)

No. 6. Bibliography on tides and certain kindred matters (Fifth instalment). (1939). (6d.)

No. 7. J. P. JACOBSEN and MARTIN KNUDSEN : Urnormal 1937 or primary Standard sea-water 1937. (1940). (1s. 4d.)

No. 8. Report of the committee on the criteria and nomenclature of the major divisions of the ocean bottom. (1940). (5s. 6d.)

No. 9. B. HELLAND-HANSEN, J. P. JACOBSEN and T. G. THOMPSON : Chemical methods and units. (1948). (2s.)

No. 10. Monthly and annual mean heights of sea-level, 1937 to 1946 and unpublished data for earlier years. (1950). (15s. 6d.)

No. 11. J. P. JACOBSEN and REX J. ROBINSON and THOMAS G. THOMPSON : A review of the determination of dissolved oxygen in sea water by the Winkler Method. (1950). (1s.)

No. 12. Monthly and annual mean heights of sea-level, 1947 to 1951, and unpublished data for earlier years. (1953). (12s.)

No. 13. Secular variation of sea-level. (1955). (4s.)

No. 14. G. BÖHNECKE : The principles of measuring currents. (1955). (3s.)

No. 15. Bibliography on Tides 1665-1939. (1955). (24s.)

No. 16. Report on oceanographical work from ocean weather ships. (1957). (3s.)

No. 17. Bibliography des marées 1940-1954. (1957). (8s.)

No. 18. Bibliography on generation of currents and changes of surface level in oceans, seas and lakes by wind and atmospheric pressure 1726-1955. (1958). (8s.)

No. 19. Monthly and annual mean heights of sea-level, 1952 to 1956, and unpublished data for earlier years. (1958). (12s.)

Procès-Verbaux :

No. 1. Cinquième Assemblées Génerale réunie à Lisbonne Septembre 1933. (1934). (1s. 6d.)

No. 2. General Assembly at Edinburgh, September 1936. (1937).*

No. 3. General Assembly at Washington, September 1939. (1940). (3s. 6d.)

No. 4. General Assembly at Oslo, August 1948. (1949)*

No. 5. General Assembly at Brussels, August 1951. (1952). (18s.)

No. 6. General Assembly at Rome, September 1954. (1955). (30s.)

These publications form a continuation of the "Bulletins de la Section d'Océanographie de l'Union Géodésique et Géophysique Internationale," of which there were 17 members, No. 1 being issued in 1921 and No. 17 in 1931 ; all out of print.

The publications can be ordered from :

The Secretariat of AIOP
Box 1038
Göteborg 4
Sweden

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The continental margin between Brittany and Ireland*

ALAN A. DAY

(*Received* 1 *August* 1958)

Abstract—The continental slope between Brittany and Ireland is steep and cut by many canyons, with the exception of the central region which forms a broad smooth spur. Scarps up to 110 miles in length are associated with the continental margin, and these, together with the steep areas of the slope proper are considered very probably to have been developed by faulting. Cores and bottom samples from the area are shown mainly to represent Recent and Pleistocene deposits, with the exception of three which represent Tertiary and possibly Cretaceous strata.

New names applied to topographic features in the area are : Meriadzek Terrace, Goban Spur, and Pendragon Scarp.

THE growth in recent years of a large amount of sounding information for the sea between Brittany and S.W. Ireland has made it possible to obtain an impression of the variety of topographic features which together constitute the continental

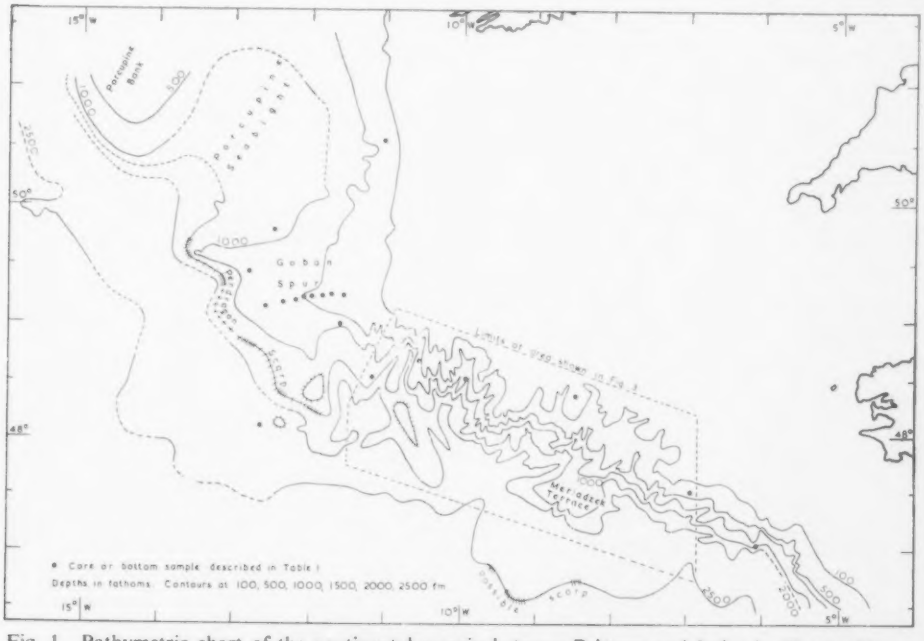

Fig. 1. Bathymetric chart of the continental margin between Brittany and Ireland. The positions of the cores and bottom samples described in Table I are shown.

slope and rise in the region. A bathymetric chart of the area is shown in Fig. 1. This chart was prepared by the author in co-operation with Dr. M. N. HILL for the

*The work described was undertaken when the author was working in the Department of Geodesy and Geophysics, Cambridge University.

general bathymetric chart of the N.E. Atlantic (HILL, 1956) and is derived from both single soundings and echo sounding profiles largely obtained by British and French naval and oceanographic research vessels.

There exist in the area three distinct topographic provinces :

(1) a province in which the continental slope is steep and is indented by many submarine canyons ; this province extends from the Bay of Biscay westwards to a line running south-west from the position 49°N, 11°W,

(2) a province of relatively simple topography extending south from latitude 49° 50′N to the western margin of province (1),

(3) a province lying to the north of latitude 49° 50′N which includes the southern slopes of the Porcupine Bank and the associated broad submarine valley.

For the sake of brevity the sea area between Brittany and Ireland will in the present paper be referred to as the "Celtic Sea" following LE DANOIS (1938), and COOPER and VAUX (1949, p. 750).

DETAILED TOPOGRAPHY OF PROVINCES

Province 1 : South-western and Southern Celtic Sea

A bathymetric survey of the upper part of the continental slope in the south-western Celtic Sea was made by the French research vessel *Président Théodore Tissier* before World War II using wire-sounding methods (France : Office des Pêches maritimes, 1934/5). A group of small-scale charts collectively covering the Celtic Sea were constructed by LE DANOIS (1948, Figs. 1-5) from the scattered soundings on the naval charts. For lack of information neither of these publications was able to show in any detail the topography of the deeper parts of the continental margin.

Recently, however, many echo-sounding profiles have been obtained in the area by the British Navy and various research vessels, making it possible to construct new bathymetric maps of the greater part of the continental slope and rise. At the present time only that section of the continental slope lying between 6° 30′W and 11° 30′W has been sounded sufficiently for the detailed topography to be revealed.

The sounding data for a large scale bathymetric chart of the province have been obtained from a number of sources. By kind permission of the Hydrographer of the Navy the author has had free access to the records of soundings preserved in the Hydrographic Department. The south-western Celtic Sea falls within the limits of Areas 29 and 43 in that Department's world-wide network of "Plotting Areas for Oceanic Soundings," and the master plotting sheets for the two areas, containing a proportion of the available soundings, have been of considerable assistance in the preparation of the bathymetric chart. A number of continuous echo-sounding profiles made by H.M.S. *Challenger*, H.M.S. *Dalrymple*, H.M.S. *Scott*, R.R.S. *Discovery II* and R.V. *Sarsia*, and lists of soundings by C.S. *Recorder* and C.S. *Norseman* were available. A detailed survey of the area centred on 48°N, 9° 30′W was made by H.M.S. *Dalrymple* in 1949, and a contour map, prepared from the results of this survey, was published by COOPER (1952a).

The total number of single soundings (including both wire and echo soundings) available from all sources is 1700 while the echograms represent 970 miles of traverses

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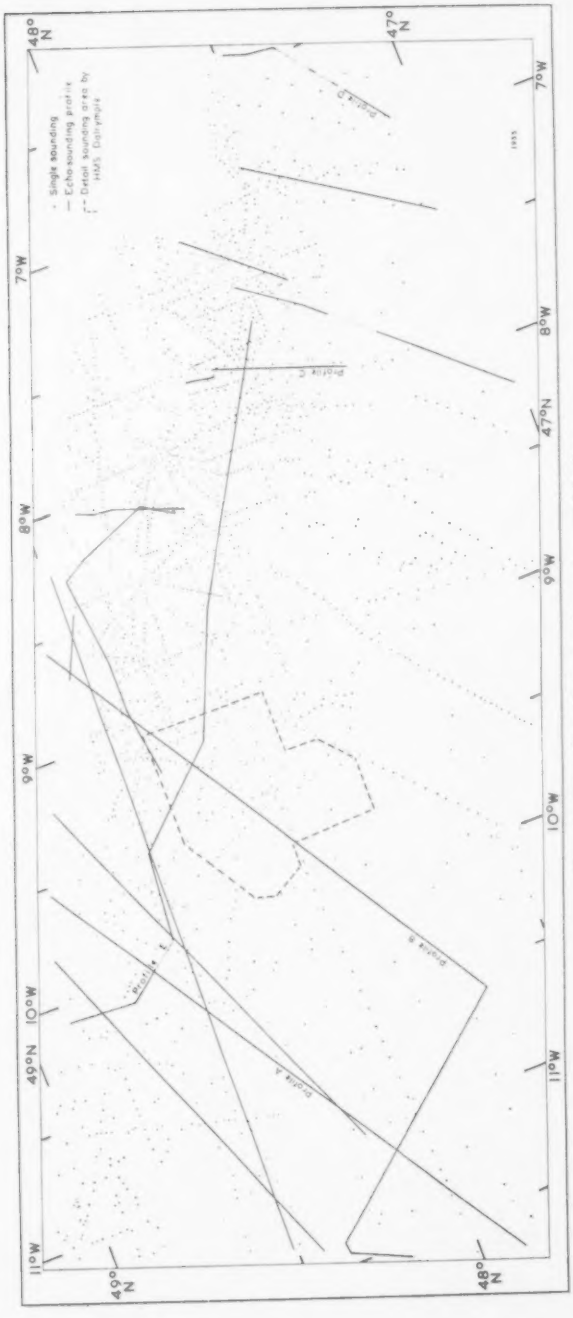

Fig. 2. Sounding data, south-western Celtic Sea.

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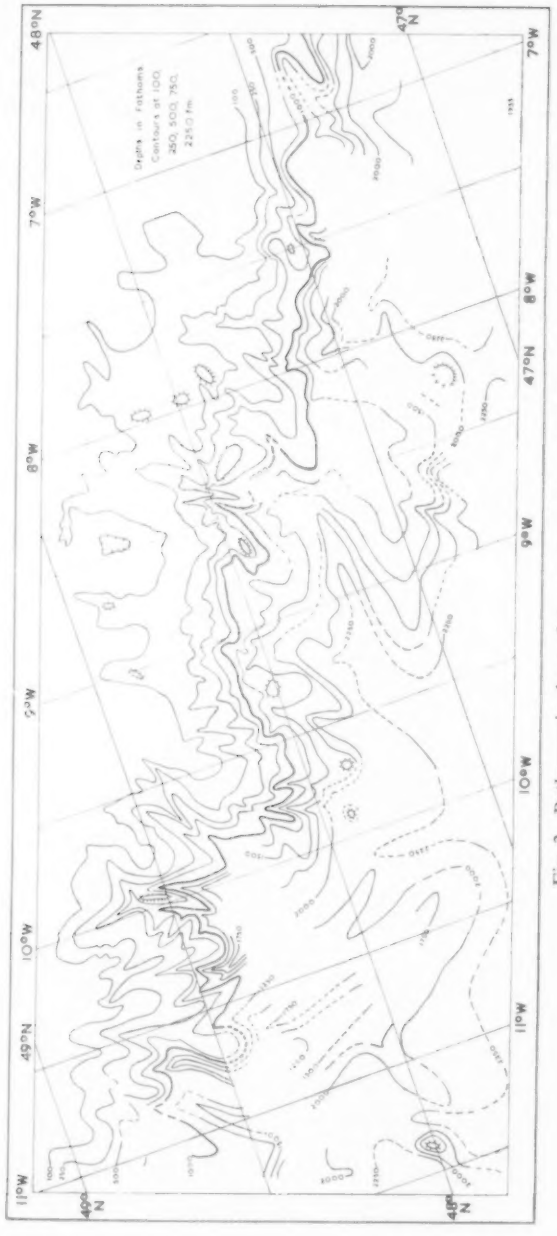

Fig. 3. Bathymetric chart of the south-western Celtic Sea.

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across the area. Fig. 2 shows the distribution of the soundings, the echo sounding profiles and the limits of the area sounded by H.M.S. *Dalrymple*.

All the echo soundings were corrected for the departures of the velocity of sound in sea-water from the standard velocities for which the various sounding machines were calibrated, using the Admiralty tables H.D. 282 (MATTHEWS, 1939). No corrections were applied to the wire soundings.

A contoured chart of the area is shown in Fig. 3. The contours have been drawn as smoothly as possible, and have been located by linear interpolation between the nearest soundings. Where the density of soundings was low, the contour affected has been shown by a broken line. In regions where soundings were sparse contours have been omitted.

The topographic features have probably been represented in Fig. 3 smoother and more regular than they are in reality. Preconceived types of topography have been avoided as much as possible. The procedure adopted by VEATCH and SMITH (1939, pp. 83,84) of deliberately fitting a stream-erosion type of topography to their data was rightly criticized by SHEPARD (1943), and care has been exercised in the construction of Fig. 3 to avoid the introduction of topographic features for which there is no basis in fact.

Errors of position and depth – Normal astronomical and dead-reckoning methods of position-finding were used throughout the surveys described above, although in the cases of the echo sounding profiles obtained by *Discovery II* and *Sarsia* it was possible to fix accurately the position of the north-eastern ends of the profiles using the " Decca " navigation aid. Although the internal accuracy of position-finding in each of the surveys and traverses is high, it might reasonably be expected that they would, in some cases, fail to fit together in areas of overlap due to slight errors in the determination of absolute position. In constructing the chart it was found that these discrepancies never exceeded about two miles, while the echo sounding profiles showed excellent agreement at points of intersection. An exception to this general good agreement among the data occurred in the short line of wire soundings by *Président Théodore Tissier* which runs south-south-west in latitude 48° 30′N, longitude 10° 45′W. This line of soundings is considered, on the evidence available, to have been taken approximately three miles to the east of the position plotted on sheet 2 of the Office des Pêches maritimes chart.

It is necessary to assume that the wire soundings were corrected by the original observers for the slope of the wire, for no records have been found stating whether this has been done. The wire soundings are not likely to be consistently in error by more than ± 5 fm. Possible errors in the echo soundings arise both from the limit to the accuracy with which the records may be read, and from random deviations of the actual vertical distribution of salinity and temperature at the site of each sounding from the generalized distributions assumed by MATTHEWS (1939) for the calculation of the Admiralty tables. An error of 5 per cent is the maximum which it is estimated could be caused in the corrections obtained from these tables ; that is 3 fm for the Kelvin and Hughes sounders calibrated for a standard velocity of 800 fm/sec (*Discovery II* and *Sarsia*), and a negligible amount for the Admiralty-pattern sounders calibrated for 820 fm/sec. The limits of accuracy of reading records from the two types of sounders are ± 2 fm for the Kelvin and Hughes type, and ± 5 fm for the Admiralty type.

An error of interpretation may arise in the case of the depths found by echo-sounding. This is due to the fact that the sound pulse sent out from the ship spreads over a wide angle, the semi-angle of the first lobe being about 18°. Many echoes may return, and the first to arrive may not necessarily have been reflected from a point vertically beneath the ship. The greatest discrepancy between the apparent and true bottom configurations occurs, in general, when profiles cross deeply-incised, steep-sided valleys, the apparent cross-section tending to be narrower and less deep than in reality. In the interpretation of the echograms it is necessary to assume that all echoes are returned from points lying in the vertical plane containing the ship's course. Circles are drawn with centres at points corresponding to the ship's position at various times and with radii equal to the echo range at these

times. The envelope of these circles is then assumed to represent the true profile of the sea floor. In the present area the greatest horizontal displacement of a depth contour necessitated by thus re-drawing the sounding profiles was found to be 0·2 mile, which is hardly appreciable on the scale of Fig. 3.

From a consideration of the possible sources of error discussed above, the distribution of the soundings, and the fact that relatively steep slopes are common in the area, the limits of accuracy in the position of any contour are estimated to be about ± 2 miles.

General description of the topography. A length of 200 miles of the continental slope is shown in the chart forming Fig. 3. This portion of the slope is approximately linear, with a general trend in the direction 290°. Gradients on the slope, except at the western limits of Fig. 3, are comparatively steep ; the increase in depth from 100 fm to 2250 fm takes place in a distance of between thirty and forty miles. The steepness of the slope is well illustrated by the echo-sounding profiles *A* to *D* reproduced in Fig. 4. The tracks along which these profiles and profile *E*, Fig. 5, were obtained, are shown in Fig. 2. Profiles *A* and *B* were obtained by H.M.S. *Scott*, profile *A* being oriented across the direction of slope. Profiles *C* and *D*, obtained by R.V. *Sarsia* are oriented parallel to the direction of slope, but profile *D* is incomplete because the rapid variations in depth along the course made it difficult for the operator to keep the sounding recorder adjusted to the correct depth-interval for recording the bottom echo.

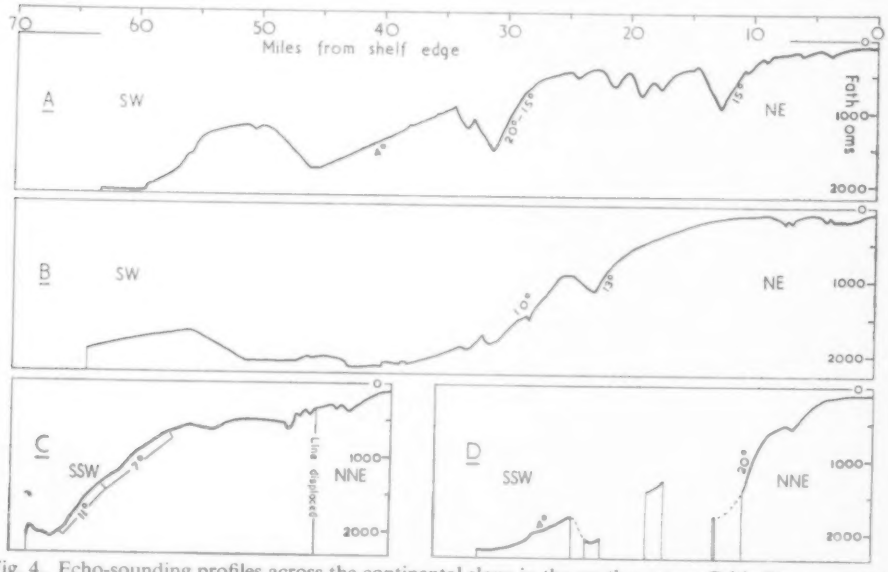

Fig. 4. Echo-sounding profiles across the continental slope in the south-western Celtic Sea, corrected for variations in salinity and temperature according to the tables of MATTHEWS (1939).

The only continental slope of comparable steepness for which detailed profiles are available is that off California (SHEPARD and EMERY, 1941). The well-known submarine escarpments in that region have slopes of about 10°-16°, and in general are slightly steeper than the slopes in the area under consideration. The steepest portion of the continental slope off the Atlantic coast of the United States appears to be that lying off Cape Hatteras, where between 100 fm and 900 fm only, the average slope is 8° (VEATCH and SMITH, 1939).

The continental slopes in the south-western Celtic Sea and off California are both markedly convex upwards. In this respect they are strongly contrasted with the slightly concave slopes off the Atlantic coast of the United States and off the Golfe du Lion (BOURCART, 1950), and also with the slightly convex slope in the Gulf of Mexico (JORDAN, 1951 ; GEALY, 1955).

Submarine canyons. The continental slope in the south-western Celtic Sea is deeply incised along its entire length by submarine canyons, many of which are branched in their upper reaches. Fig. 7 shows that the overall pattern of canyons is markedly dendritic. Twenty-one canyons or canyon systems can be distinguished with certainty, and it is possible that a few more may exist in those areas of the slope which are poorly sounded. Profiles *A* and *B* in Fig. 4 incorporate sections across several canyons. These profiles together with others whose courses are shown in Fig. 2, demonstrate that most canyons are V-shaped in transverse section and are also steep-walled. In longitudinal profile the canyons are closely comparable with the American canyons.

The data are insufficient to show whether any barred basins are present along the courses of the canyons, but the complex area centred on 48° 35′N, 10°W and known to the French trawlermen as " Le Dédale " (labyrinth), may possibly enclose a barred basin at a depth of about 800 fm.

To the south-east of the area investigated in detail the continental slope retains its steep and markedly convex character. It is also deeply incised with steep-walled canyons. These features are illustrated by the north-south profile, taken in longitude 5° 36′ and at 45° to the true direction of slope, by BROWNE and COOPER (1950, Fig. 4 (c)).

Other major topographic features. Three large topographic features are associated with the continental slope in the area. The existence of the first feature (centred on 47½°N, 8½°W) is well established, although, as indicated on Fig. 3, its exact configuration is in part uncertain owing to a shortage of soundings. The feature may be likened to a large terrace projecting southward from the adjacent parts of the continental slope. The surface of the terrace is gently undulating and lies at a depth of 1100–1200 fm. The gradient of the slope above the terrace, between the 250 fm and 1000 fm contours is approximately equal to that between similar levels along the remainder of the continental slope in the area. Likewise the gradient of the south-western face of the terrace, between the 1250 fm and 2000 fm contours corresponds to that between similar levels elsewhere in the slope. An echo-sounding profile across this face shows it to have a slope of 12° between 1400 and 2400 fm. The north-western and south-eastern faces of the terrace are less steeply inclined than the south-western face, except near their junctions with the main continental slope, where deep canyons appear to be present. I propose that the name *Meriadzek Terrace* be applied to the feature. (Meriadzek was an early Cornish saint).

The exact form of the second topographic feature (centred on 48°N, 10° 40′W) is not as yet very well defined, but there is reason to believe, on the basis of the available information, that it is an elongated seamount or ridge rising at its northern end nearly 5000 ft above the deep ocean floor. Profiles across this feature are shown on the south-western extremities of profiles *A* and *B*, Fig. 4.

The continental rise in this province extends, in general, with a gentle gradient from about 2100 fm down to the 2700 fm plain that forms the deep ocean floor in the Bay of Biscay and to the west. The gentle gradient of the continental rise is interrupted

south of the Meriadzek terrace. Four echo-sounding profiles crossing the area in question reveal (Fig. 6) that the sea-floor falls gently southwards from the base of the steeply-sloping face of the terrace to a depth of 2250 to 2450 fm, and then rises again to a rounded crest at 2100 to 2250 fm. On all four sounding profiles the rounded crests are bordered to the south by moderately steep scarps. The scarps are tentatively considered to represent a continuous south-facing escarpment, the probable course of which is shown on Fig. 1. The height of the scarp on each sounding profile is 350 fm. The maximum slope, 10°, occurs in the centre of the known length of the scarp ; at the eastern end of the scarp its slope is 4° and at the western end $6\frac{1}{2}$°. Sounding lines taken 25 miles to the east and 20 miles to the west of the known limits of the escarpment show no trace of the feature.

Beyond the scarp, to the south and south-west, the sea floor reassumes a gentle gradient towards the centre of the ocean basin.

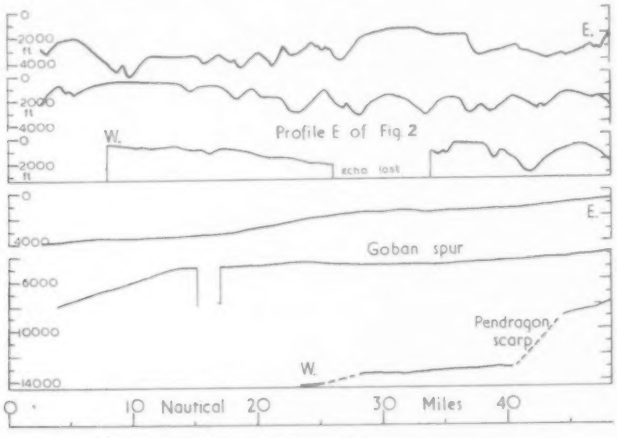

Fig. 5. Echo-sounding profiles across the continental slope in the south-western Celtic Sea (upper profile) and western Celtic Sea (lower profile).

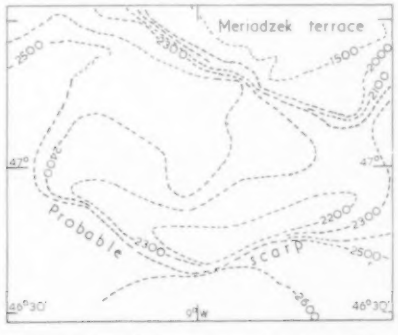

Fig. 6. Submarine topography of the area at the foot of the Meriadzek Terrace.

Province 2 : *West central Celtic Sea*

One north-south and five east-west echo sounding profiles cross this area. A representative profile, obtained by *Discovery II*, is shown in Fig. 5. This illustrates the gentle, relatively smooth slope between the continental shelf edge and the 1500 fm

contour. Topographically the feature resembles a very large, smooth spur whose surface dips northward into the Porcupine Seabight, very gently westward to a steep scarp, and, with a more irregular surface, southwards to the area strongly dissected by canyons. Using a name from Celtic mythology, the spur will be referred to as *Goban Spur*.

Every echo-sounding profile available for this area crosses a steep scarp west or south-west of the gentle slopes of the spur. The general consistency of the heights and average inclinations of the scarps suggests that they represent a continuous feature that bounds the Goban Spur on the west and south-west. The probable course of the scarp is indicated on Fig. 1.

The existence of the scarp was first indicated by BRADLEY (1940, Fig. 1) in a section drawn along the course of a transatlantic cruise of the C.S. *Lord Kelvin*. No suitable ship's name is available for the scarp, and the name *Pendragon Scarp* is therefore proposed. (Pendragon was the father of King Arthur in Celtic legend).

The Pendragon Scarp appears from Fig. 1 to be at least 110 miles long and is thus an important bottom feature. The depth to the upper boundary of the scarp varies between 1050 and 1450 fm, being least in the north ; the height of the scarp is in most cases betweeen 400 and 600 fm, but decreases to 250 fm at its northern end. To the north the scarp merges into the moderately steep slope in the western reaches of the Porcupine Seabight. The slope of the scarp, as determined from the sounding profiles, is uniformly about 10°, but decreases at the northern end of the scarp. The southern end of the scarp appears to be cut across by the large embayment at the western end of the canyon area in the south-western Celtic Sea.

Topographically, the Pendragon Scarp bears a close resemblance to the Sigsbee and West Florida Scarps in the Gulf of Mexico. These scarps also cut across gently sloping areas (see GEALY, 1955, p. 211, and JORDAN, 1951).

West of the Pendragon Scarp the sea floor slopes gently to depths of about 2650 fm in longitude 16°W.

Province 3 : *Porcupine Bank to Great Sole Bank*

The very wide valley separating the Porcupine Bank from the main continental slope south-west of Ireland has been named the Porcupine Seabight by the British National Committee for the Nomenclature of Bottom Features. The floor of the seabight appears from the available evidence to be smooth. The continental slope which forms the eastern margin of the seabight is cut by short canyons (COOPER, 1952b). The flanks of the Porcupine Bank are smooth and gently sloping, except on the lower reaches of the western flank, where a scarp is indicated by the available sounding profiles.

CORES AND BOTTOM SAMPLES FROM THE CONTINENTAL MARGIN

Sixteen cores and three bottom samples from the area have been examined with regard to their lithology and foraminiferal content. The results of this study are summarized in Table I.

The descriptions of lithology depend partly on determinations of calcium carbonate content in samples of the dry, salt-free material, and follow the classification proposed by REVELLE (1944, p. 16) and extended by ARRHENIUS (1952, p. 11). The age determinations are based on the recognition of pebbly glacial layers and on the identification

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Table 1. Descriptions of Cores and Bottom Samples from the Continental Margin

Station No.	*Position Lat. N Long. W*	*Depth (fm)*	*Section of core* (cm)*	*Description of sample (see note on nomenclature in text)*	*Geological age*
Dy 2992	49° 48′ 12° 28′	1140	0- 5 5- 18 18-165	Light grey foraminiferal chalk ooze Brown-grey foraminiferal marl ooze Brown mud	Pleistocene–Recent
Dy 2997	49° 26′ 12° 49′	781	0- 33 33-153	Grey foraminiferal marl ooze Brown mud	Pleistocene–Recent
Dy 3108	49° 15′ 11° 35′	175	0- 46	Dark green fine sand with small pelecypods	Recent
Dy 3109	49° 15′ 11° 43′	305	0- 44	Green-grey foraminiferal silt	Recent
Dy 3110	49° 14½′ 11° 50′	400	0- 15 15- 49	Greenish grey chalk ooze Brown mud	Pleistocene (?)–Recent
Dy 3111	49° 14′ 11° 58′	435	0- 31 31- 34 34- 47 47- 55	Grey foraminiferal chalk ooze Brown-grey mud Pteropod-foraminiferal chalk ooze Brown-grey mud	Pleistocene–Recent
Dy 3112	49° 13′ 12° 05′	460	0- 43 43- 53	Grey foraminiferal chalk ooze Grey-brown mud	Pleistocene (?)–Recent
Dy 3113	49° 12·5′ 12° 12′	512	0- 6 6- 61	Grey-brown foraminiferal marl ooze Grey-brown mud	Pleistocene–Recent
Dy 3114	49° 11′ 12° 23′	571	0- 30 30- 37 37- 50 50- 61 61- 67	Grey foraminiferal mud Grey foraminiferal marl ooze Grey foraminiferal mud Grey foraminiferal marl ooze Grey foraminiferal mud	Pleistocene–Recent

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Table 1—continued

Station No.	*Position Lat. N Long. W*	*Depth (fm)*	*Section of core* (cm)*	*Description of sample (see note on nomenclature in text)*	*Geological age*
Dy 3115	49° 09′ 12° 36′	740	0- 10 10-115 115-126	Grey foraminiferal chalk ooze Grey-brown foraminiferal mud Grey foraminiferal chalk ooze	Pleistocene–Recent
Dy 3135	47° 06′ 6° 06′	997	0-160	Brown to dark grey foraminiferal mud with thin sandy layers	Pleistocene–Recent
Cr 5	48° 22·4′ 8° 28·9′	99	0- 6	Fine white sand with a few broken shells and foraminifera	Recent
Cr 29	48° 06·2′ 12° 40·9′	2080	0- 10 10- 48	Grey-brown foraminiferal chalk ooze Brown foraminiferal mud (Core shows signs of extensive churning by burrowing organisms)	Pleistocene (?)–Recent
Cr 30	48° 39′ 10° 35′	776	0- 53	Brown foraminiferal marl ooze with layer of small pebbles at 14 cm	Pleistocene (?)–Recent
Cr 33	48° 32·3′ 11° 10′	1180	0- 11 11- 42	Grey foraminiferal chalk ooze Brown foraminiferal mud	Pleistocene–Recent
Cr 46	48° 59′ 11° 38′	818	0- 37 37- 41	Brown mud Brown grey foraminiferal marl ooze	Pleistocene (?)
Ck 1/51	50° 32·4′ 11° 01·4′	410	L	Brown foraminiferal mud	Recent
Sa 1	47° 55′ 7° 41′	125	D	Coarse gravel and large shells with a little sand	Quaternary
Sa 2	47° 31′ 6° 58′	280	C	Clean, white, hard, chalk-fragments and chalky sand (Extremely small sample)	Possibly Cretaceous, or Tertiary

*The equipment used is indicated by the symbols : C, corer (only when sample was very small) ; D, dredge ; L, sounding lead.

of numerous species of foraminifera with a few species of pteropoda. (References:—foraminifera : CUSHMAN, 1918-31, 1950 ; CUSHMAN and HENBEST, 1940 ; PHLEGER, 1954 ; pteropoda : REHDER, 1942 ; TESCH, 1946).

Two cores and fourteen bottom samples from the area have been described by previous authors. These descriptions, some of considerable antiquity, refer to :
Lord Kelvin cores (Lk 12 and 13) – BRAMLETTE and BRADLEY (1940), CUSHMAN and HENBEST (1940), PIGGOTT and URRY (1942) ;
Porcupine samples (Pn 35-37, 39-43) – BRADY (1884), CARPENTER *et al.* (1869) ;
Alsace sample – BOURCART and MARIE (1951) ;
Monarch sample – WISEMAN and OVEY (1950) ;
Irish Fisheries dredgings (nos. 25 and 26) – COLE and CROOK (1910) ;
Two samples (not numbered) – BAILEY (1885).

The positions of all the cores and samples are shown on the general bathymetric chart of the continental margin (Fig. 1). The positions of those samples obtained in the south-western Celtic Sea are also indicated on Fig. 7.

Of all the samples described by previous authors or in Table 1, only three are pre-Quaternary in age : the *Alsace* sample (Oligocene), the *Monarch* sample (Upper Cretaceous – Eocene), and the *Sarsia* sample Sa 2 (Upper Cretaceous or Tertiary). Reference to Fig. 7 suggests that the first two of these samples were possibly derived from within submarine canyons, although this conclusion is tentative owing to the uncertainty of the local bathymetry in the case of the *Alsace* sample, and of the geographical position of the *Monarch* sample. The *Sarsia* sample was obtained from a steep slope extending from the shelf edge to a depth of several hundred fathoms.

The pre-Quaternary samples all represent types of sediment which could have been deposited on the continental slope in depths similar to those in which they now occur, though there remains the possibility that these samples represent loose material that has drifted down-slope from its original outcrop or may have been transported from elsewhere.

The presence of Recent or Pleistocene sediments in 33 samples out of 36 suggests that the greater part of the continental slope has a mantle of sediment of Quaternary age, and proves that sedimentation has continued in the area at least since about middle Pleistocene times. The evidence of the *Alsace* and *Monarch* samples, if it is accepted, suggests further that sedimentation has continued in at least part of the area since the Upper Cretaceous or early Tertiary. A detailed discussion of the significance of the types of sediment that have been found in the coring work is not required for our present purposes, and is therefore reserved for a later publication.

In the occurrence over the greater part of the slope of Quaternary sediments and the apparent scarcity of outcrops of older rocks, the continental margin between Brittany and Ireland resembles the corresponding features on the Atlantic and Gulf Coasts of the United States, but contrasts strongly with the continental margin off California.

ORIGIN OF THE TOPOGRAPHY

The topography of the continental margin is complex and presents difficulties of interpretation that arise, in part, from our lack of knowledge of those tectonic processes which may affect the boundary zones between continents and oceans. A fault origin may reasonably be proposed for some topographic features, but for other features it is not possible to find unequivocal explanations.

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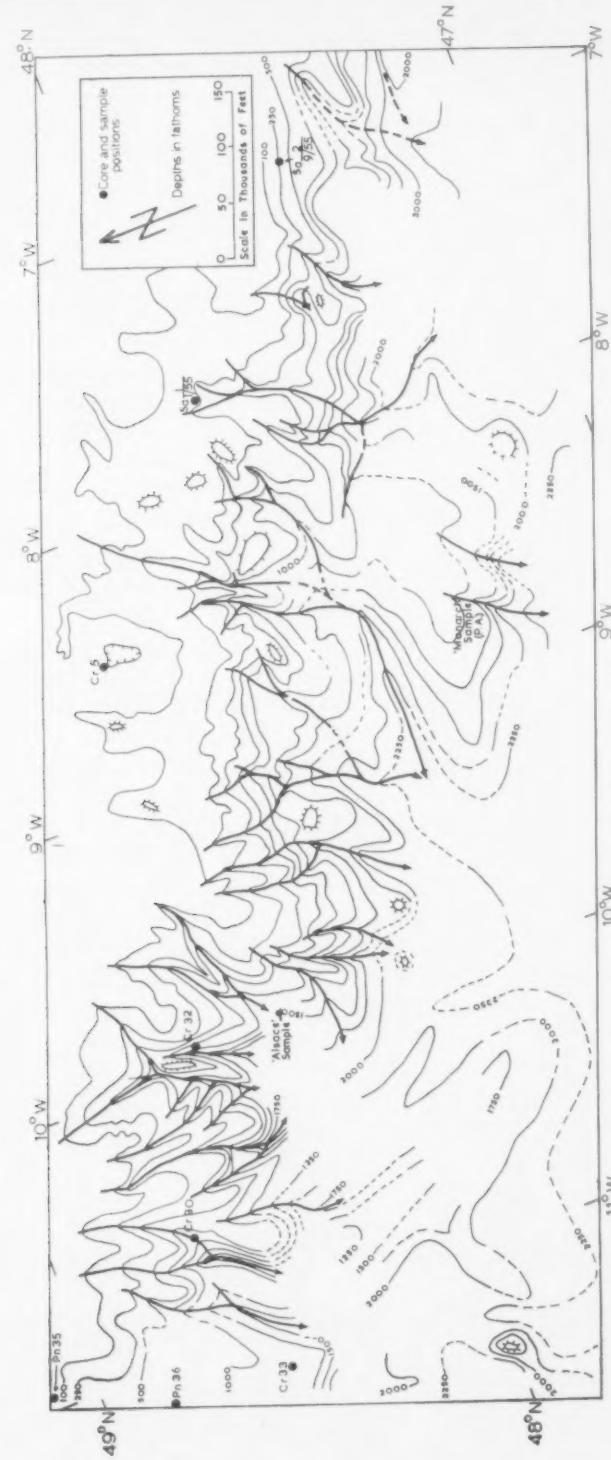

Fig. 7. Bathymetric chart of the south-western Celtic Sea showing the position of cores and bottom samples and demonstrating the dendritic pattern of submarine canyons.

South-western and southern Celtic Sea – In discussing the origin of the topography of this province it will be convenient to consider the less important topographical features first.

The large feature, possibly a seamount, that lies at the foot of the continental slope at about 10½°W does not appear to be related to the surrounding topography. In the absence of sufficient sounding data and of any coring information it would hardly be justified to guess the origin of the feature. It is, however, reminiscent of the elongated seamounts which lie at the foot of the continental slope off California and have been described by SHEPARD (1941).

The origin of the basin-like feature which lies at the foot of the Meriadzek terrace is rather obscure. The feature may have been the result of movements associated with vulcanism on the deep-sea floor, or perhaps with horizontally-acting compressional forces, which would be capable of forming a synclinal depression in the basement that would presumably be reflected in the sediments above. Detailed sounding and coring are required to discover the true nature of this feature.

Because the submarine canyons that are so plentiful in this province have a marked dendritic pattern, they cannot primarily owe their origin to structural causes (such as local folding or faulting), but must largely have arisen by the erosion of a pre-existing, relatively smooth surface. Clearly this supposed surface must have possessed an initial gradient greater than that of the western part of Goban spur, for example, because otherwise a much greater development of canyons ought now to exist on the spur. It is probably correct to assume that the original surface of the continental slope was approximately the same as that obtained by taking the envelope of the ridges between the canyons. The depth to which the canyons appear to have cut into the sedimentary layer is in places equivalent to nearly half the total thickness of post-Carboniferous sediment determined by seismic methods (DAY *et al.*, 1956, Fig. 16).

On the balance of the evidence the canyons are considered to represent, at least in their upper reaches, drowned subaerial valleys which are kept open by submarine sliding of newly deposited sediments and by turbidity currents originating at or near their sandy upper limits. The canyons would be classified as " intermediate " types according to KUENEN's scheme of classification (KUENEN, 1953).

Also, the gradients on the continental slope in the province attain values that are too great to be explicable otherwise than by faulting or by a sharp down-bending of the crust at the continental margin. The hypothesis of faulting has been favoured by SHEPARD (1941) in the case of the California continental slope, and by HARRISON (1955, p. 295) and STAUB (1951, p. 68) in the case of the steep slopes on the west side of the Ionian Sea. On balance, the evidence suggests that faulting has been the more important mechanism in the production of the steep, highly convex continental slope in our area. The Meriadzek terrace is a peculiar topographical feature whose origin cannot reasonably be ascribed to erosion or down-bending, but which may readily be explained on the hypothesis that the process of faulting left an arched-up block, whose upper surface now lies at a depth of approximately 1200 fm. (An alternative but most unlikely explanation of the nature of the Meriadezk terrace is that it is a feature in the Palaeozoic floor covered by a relatively thin mantle of sediment).

There is some evidence that the continental slope maintains its convex character and high gradient to the south-east, in the Bay of Biscay. Also the continental slope

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is very nearly straight between the Goban spur and the latitude of Bordeaux. These facts suggest that faulting may have taken place along the entire length of the continental margin between the limits mentioned.

In the absence of any clear evidence on the subject it is impossible to deduce the time at which the faulting took place.

West-central Celtic Sea – The smooth topography and low surface gradients on Goban spur suggest that the spur consists of a sedimentary pile resting on a basement which also has a smooth surface configuration. Seismic work in the area indicates that beneath the Goban Spur the " Palaeozoic floor " rises to the north from the axial region of the English Channel geosyncline (DAY *et al.*, 1956, Fig. 14). It therefore seems possible that the spur is the surface expression at the continental margin of the tectonically " positive " area of the Palaeozoic floor that extends south-west from Cornwall.

It is obvious that the Pendragon Scarp cannot have been produced by normal processes of sedimentation or erosion. The steep slopes on the scarp, and its relationship to the surrounding topography suggest, rather, that it is the surface outcrop of a fault cutting across the sedimentary pile and the underlying basement. The fault, if the scarp is correctly interpreted as such, does not appear to be active at the present time, for the International Seismological Summary has not listed any earthquake epicentres in the area (up to Dec. 1946).

The cores Lk 12 and 13 described by BRAMLETTE and BRADLEY (1940), were collected from the foot and the top of the scarp, respectively, both cores consisting of an apparently unbroken sequence of later Pleistocene and Recent sediment. The thickness of the individual beds is much less in the core raised from the top of the scarp than in the one obtained at the base, suggesting that the sequences found in the cores were formed in the topographical environment now existing and certainly not on a flat oceanic floor. In the latter case there would be no reason to expect the thicknesses of the component layers to be so markedly different, but in the former case sliding of sediment from the scarp down to the lower levels would occur and thus produce the discrepancy in thickness. It is not known whether rock outcrops on the face of the scarp.

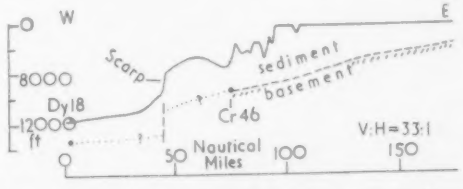

Fig. 8. Hypothetical section across the continental margin at 48° 50'N, showing the relationship of sea-floor topography to seismic results.

On the basis of the available evidence, therefore, it seems reasonable to conclude that the Pendragon Scarp was developed by moderate faulting in the upper part of the crust in the Tertiary or an earlier period. The faulting may have been associated with the widespread vertical movements which occurred during the Tertiary vulcanism. Fig. 8 illustrates the fault hypothesis and includes information from seismic work (HILL and LAUGHTON, 1954 ; DAY *et al.*, 1956).

General – Faulting has been proposed by several authors to explain the origin of unusually steep continental slopes. In each case it appears that the faulting is assumed to be of the high-angle type, but the circumstances which are supposed to have given rise to the faulting are varied. MENARD and DIETZ (1952), for example, have attempted to explain the origin of a number of submarine fault scarps off the West Coast of the United States by a consideration of the pattern of *shear* faulting which appears to be affecting the entire north-east Pacific region. In the present case there is no regional evidence that horizontal tectonic forces are in operation, and therefore appeal must be made to vertical forces and the effects of *tension* in order to explain the formation of the faults along the continental margin between Brittany and Ireland.

Acknowledgements—I wish to express my thanks to the Hydrographer of the Navy, Dr. M. N. HILL, Dr. J. C. SWALLOW, and Dr. L. H. N. COOPER for the provision of sounding data. I am further indebted to the Directors of the National Institute of Oceanography and the Marine Biological Association, Plymouth, for sea-going facilities in R.R.S. *Discovery II* and R.V. *Sarsia* respectively.

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The lobster, *Homarus americanus*, and the red crab, *Geryon quinquedens*, in the offshore waters of the western North Atlantic

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(*Received* 7 *October* 1958)

Abstract—A population of lobsters, large enough to support commercial fishing, is present off the east coast of the United States along the outer shelf and upper slope between the eastern part of Georges Bank and the offing of Delaware Bay. This area at depths of roughly 60-250 fm (110-450m), is about 400 miles long and 5-10 miles wide. Lobsters are more plentiful along the eastern half of this stretch than to the west and south. Although there are all sizes from " shorts " to very large, a much greater percentage than in the shoal water populations are large.

Prior to 1953, the New England trawler fleet took only small numbers of lobsters, incidental to their catch of fish, in deep water, but since then several otter trawlers have been fishing offshore exclusively for lobsters and have made substantial catches. However, the recorded total annual catch in deep-water up to 1956 has not exceeded 1 per cent of the total annual catch taken by the inshore pot fishery.

The otter-trawl catch of lobsters off New York and New Jersey, small prior to 1947, now exceeds the catch taken with pots, but the fishery as a whole is of small magnitude compared with that to the north and east.

There is no evidence thus far of a definite migration of lobsters between inshore and offshore areas but no doubt most of them wander from time to time in search of food (or perhaps for no particular reason).

A deep-water crab (*Geryon quinquedens*), as yet unexploited, might become the source of a commercial fishery along the North and Middle Atlantic coast. It inhabits depths between 150-700 fm (275-1280 m), or more, and ranges from the offing of Nova Scotia to Virginia and southward, perhaps in diminishing numbers, at least to Cuba.

THE LOBSTER, *Homarus americanus*

EVER since the introduction by the commercial fishery of the beam trawl in 1891 and of the otter trawl in 1905* in American waters, lobsters have been taken with this gear as an incidental part of the fish catch along our North Atlantic coast. The beam trawl long ago ceased to be an important adjunct to our fisheries but the number of otter trawlers operating off New England has steadily increased from 7 vessels in 1912 to 44 in 1920 (RADCLIFFE, 1922, p. 51) and to 603 vessels of 5 tons or over in 1955. As a rule the catch of lobsters taken by trawlers per trip has been very small, ranging from a few individuals to about a hundred pounds, and occasionally to a thousand pounds or more, as for example the 1850 lb landed by *Cap'n Bill II*, April 3, 1952, fishing for fluke (*Paralichthys*) in 60-65 fm (110-120 m) south-west from No Mans Land. On some trips none are caught. The aggregate annual lobster catch by all trawlers engaged primarily in fishing, not lobstering, is probably substantial although amounting to but a very small percentage of that taken by the regular lobster trap fishery.†

*For a discussion of the earliest fishing in our waters, see ALEXANDER *et al.*, 1915.

†There are no adequate statistical records of these incidental catches made by otter trawlers, for it has been customary, when enough lobsters are brought in to warrant selling, to divide the proceeds among the crew, apart from their share in the sale of fish. These lobsters are not reported in the vessel's catch.

Most of the early otter-trawl fishing was not much deeper than about 80 fm (146 m) and many of the lobsters caught were very large. More recently depths down to 125 fm (228 m), and beyond, have been trawled by part of the fishing fleet and increasing amounts of lobsters have been taken along with the fish catch, not only very large ones, but also medium-sized and small ones as well. A large proportion of these offshore lobsters are caught in depths well beyond the realm of the pot fishery.

One of the earliest, if not the first, published statistical record of otter-trawl caught lobsters landed along our coast was for 7985 lb listed for New York in 1921 (U.S. BUREAU OF FISHERIES, 1924, p. 85). Fishery statistics for the Middle Atlantic and New England states are not available for all years since 1921. Thus, the next records available are for 1440 lb landed in Connecticut in 1925 and for 3465 lb in 1926, part of them by the shore fishery and part by the so-called vessel fishery.

Table 1. *Catch of lobsters for the New England States, from* 1928 *to* 1956 *with a comparison between the inshore pot fishery and offshore otter trawling**

Year	lb		*Percentage of total catch taken by trawls*	*No. of pots*	lb
	Pots	*Otter trawls*			*Aver. per pot*
1928	11,603,328	351	†	334,574	34·6
1929	10,322,262	204	†	345,824	29·8
1930	12,356,121	1201	0·01	332,791	37·1
1931	11,311,985	34	†	357,704	31·6
1932	10,278,272	85	†	341,595	30·0
1933	9,086,243	1882	0·02	319,460	28·5
1935	10,847,300	5000	0·05	289,437	37·5
1937	10,931,400	4500	0·05	306,130	35·7
1938	11,397,100	10,700	0·10	302,510	37·6
1939	11,303,600	7900	0·07	330,246	34·3
1940	11,157,900	7400	0·07	328,988	33·9
1942	11,791,300	200	†	267,342	44·2
1943	15,650,800	400	†	290,649	53·7
1944	17,203,400	13,300	0·08	312,934	55·0
1945	22,237,800	29,100	0·13	464,826	47·8
1946	22,819,300	4500	0·02	572,098	39·9
1947	23,310,900	5500	0·03	660,961	35·3
1948	20,206,800	19,500	0·10	598,425	33·8
1949	23,980,500	14,000	0·06	601,786	39·8
1950	22,546,700	12,000	0·05	570,635	39·5
1951	25,528,100	6000	0·02	507,927	50·3
1952	24,309,800	13,100	0·05	540,216	45·0
1953	27,032,100	103,600	0·40	564,665	47·9
1954	26,273,000	167,600	0·60	618,279	42·5
1955	27,510,500	107,500	0·39	665,269	41·4
1956	24,932,100	227,500	0·91	648,337	38·5

*Based on annual reports of the U.S. Bureau of Fisheries published from 1929 to 1941 for the years 1928-1938 and the U.S. Fish and Wildlife Service published from 1942 to 1956 for the years 1939 to 1954. Statistics for 1955 and 1956 are based on data furnished by Mr. Dwight L. Hoy of the U.S. Fish and Wildlife Service.

†Less than 1 one-hundreth of 1 per cent.

Beginning in 1928, the catch statistics were entered regularly for otter-trawl caught lobsters landed in New England (Table 1) and in 1929 in New York and New Jersey (Table 3) (U.S. BUREAU OF FISHERIES, 1931), although in some years the amounts were trifling. If the reported landings of otter-trawl caught lobsters, prior to 1953, were multiplied by say 10 or 20 they would more closely approximate the actual

quantities brought to port (Footnote 2, p. 266). Even if corrected in this way, the trawl catch would scarcely amount to 1 per cent of the total catch in most years.

It is of interest to find that an average annual catch of 42·5 lb of saleable lobsters per pot was recorded for the 14 years from 1943 to 1956 as compared with 34·4 lb for the 12 years for which statistics are available for the period from 1928 to 1942 (Table 1). While some unknown factors are involved in this comparison, such as the number of days the pots may have fished during each of these periods, the effects of economic conditions, etc., nevertheless there appears to be no indication that the population suffered from overfishing. Similarly, TAYLOR *et al.* (1957, p. 325) in discussing the fluctuations in lobster landings, which in Maine increased from 7·6 million to 19·1 million lb per year between 1940 and 1945, concluded " that the increased catch was caused by an increase in abundance rather than by an increase in the amount of fishing", possibly due to the warming of the coastal waters north of Cape Cod since 1940. Increased landings occurred not only along the coast of Maine but also in Massachusetts and Nova Scotia.

The first evidence that lobsters inhabit depths well beyond 100 fm (183 m) along our coast was furnished by a catch of 3 small ones trawled in 195-210 fm (356-384 m) by the *Caryn* of the Woods Hole Oceanographic Institution, on June 29, 1948, about 85 miles SSW of Martha's Vineyard (lat. 39° 55′N., long. 70° 39′W.). This was followed by a catch taken nearby on October 16, of 23 lobsters, 5½ to 9 in. long (measured from the end of the rostrum to the end of the tail) in 167-250 fms (305-456 m) and by 13 others, 7 to 14 in. long, trawled September 10, 1949, in 100-150 fm (183-274 m).

On a cruise of the *Albatross III*, May 11-17, 1950, a number of hauls* were made in depths beyond 100 fm (183 m), several of which yielded fair numbers of lobsters. Of particular interest are the following :

No. of lobsters	*Wt.* (lb)	*Locality*	*Depths* (fm)	(m)	*Duration of drag* (hr)
26	2–18	39° 42′N, 71° 57′W	145–210	265–384	1
6	1½–6	39° 50′N, 71° 44′W	107–137	196–250	½
11	1½–7	39° 54′N, 71° 35′W	112–142	205–260	½

In June–July 1952 and 1953, during the course of deep-water exploratory fishing with the chartered trawler *Cap'n Bill II*, the author discovered off southern New England areas that gave promise of yielding substantial numbers of lobsters and of supporting an offshore otter-trawl fishery. On July 8, 1954, *Atlantis* made several good hauls of lobsters, followed by 6 hauls made by *Caryn*, September 2–3, 1956, in the same general area trawled by *Cap'n Bill II* in 1952 and 1953†.

*An Iceland trawl with a 78 ft head-rope and 114 ft foot-rope, but without rollers, was used on this cruise.

†Most of these hauls fished at the bottom for about 30-40 min with a towing speed of 2·5 knots. In 1952 the trawls used measured 35 and 50 ft respectively at the foot-rope and in 1953-1956, 50 and 60 ft, the head-rope being about 18 per cent shorter in each case. The body and wings were of 3 in. and the cod end of 1½ in. stretched mesh.

Table 2. Catches of lobsters made by Cap'n Bill II, Atlantis *and* Caryn *during* 1952-1956 *along the outer shelf and upper continental slope from the offing of Georges Bank to Virginia, arranged by longitude*

Station	*Date*	*Lat.*	*Long.*	(fm)	*Lobsters*		*Bottom† Temp* (°F)
					No.	*Length* (in.)*	
200	July 25, 1953	40° 46′	66° 48′	100–105	1	18	53
201	July 25, 1953	40° 45′	66° 51′	85–87	2	14–16	52
116	July 29, 1952	40° 46′	66° 53′	85–87	1	14	
117	July 29, 1952	40° 46′	66° 55′	67–71	1	11½	
194	July 24, 1953	40° 41′	67° 15′	52–55	4	12–18	
209	July 26, 1953	40° 15′	68° 28′	85–92	1	8	50
54	July 10, 1952	39° 55′	69° 25′	185–235	24	8–13	
81	July 16, 1952	39° 55′	69° 25′	190–220	1	10	
82	July 16, 1952	39° 58′	69° 28′	105–135	6	6–9½	
83	July 16, 1952	39° 59′	69° 32′	87–90	7	7–13	
84	July 16, 1952	39° 59′	69° 35′	82–85	14	8–17	
85	July 16, 1952	40° 02′	69° 37′	75–90	30	6–18	
45	June 26, 1952	39° 52′	69° 43′	180–260	5	7¼–12	
217	July 28, 1953	39° 57′	69° 51′	90–100	30	7½–17	
218	July 28, 1953	39° 59′	69° 54′	80–87	16	6½–20¾	53
219	July 28, 1953	39° 55′	70° 03′	110–115	4	9–9½	52
38	June 25, 1952	40° 04′	70° 12′	190–225	3	7½–13	
37	June 25, 1952	40° 01′	70° 18′	160–170	3	6–10	
35	June 25, 1952	40° 02′	70° 24′	105–110	1	7½	
34	June 25, 1952	40° 03′	70° 25′	110–125	1	7⅝	
33	June 25, 1952	40° 00′	70° 30′	160–200	1	7½	
255	July 8, 1954	40° 06′	70° 31′	100	4	**	57
254	July 8, 1954	40° 04′	70° 33′	70–85	16	**	54
256	July 8, 1954	40° 04′	70° 33′	70–73	64	**	60
264	Sept. 2, 1956	40° 04′	70° 33′	65–80	9	**	
221	July 29, 1953	40° 04′	70° 34′	70–75	57	7–16¼	54
32	June 24, 1952	39° 58′	70° 36′	150–160	10	6½–12½	
252	July 8, 1954	40° 04′	70° 37′	70–72	64	**	58
253	July 8, 1954	40° 05′	70° 37′	70	24	**	59
222	July 29, 1953	40° 03′	70° 39′	80–93	36	7–20½	52
260	Sept. 2, 1956	40° 04′	70° 39′	70	14	**	
251	July 8, 1954	40° 04′	70° 41′	75	38	**	58
223	July 29, 1953	40° 00′	70° 42′	150–155	18	6½–9¾	46
227	July 29, 1953	40° 02′	70° 42′	110	5	7–9	49·5
261	Sept. 2, 1956	40° 04′	70° 42′	75	15	**	
266	Sept. 3, 1956	40° 04′	70° 44′	70–80	24	**	
267	Sept. 3, 1956	40° 04′	70° 47′	81–83	10	**	
268	Sept. 3, 1956	40° 04′	70° 50′	75	17	**	
19	June 23, 1952	39° 57′	71° 13′	175–180	6	8–11	
15	June 22, 1952	39° 56′	71° 22′	175–200	8	6½–9½	
14	June 22, 1952	39° 56′	71° 26′	150	8	7¾–16	
13	June 22, 1952	39° 55′	71° 27′	180–190	13	6¾–11½	
4	June 21, 1952	39° 32′	72° 01′	185–225	4	8–11½	
162	July 1, 1953	39° 36′	72° 04′	81–83	5	9–13	
161	July 1, 1953	39° 34′	72° 05′	120–135	8	9–16	
155	July 1, 1953	39° 22′	72° 22′	76–79	2	12–13	53
130	June 27, 1953	38° 45′	73° 08′	50–55	15	9–16	
150	June 30, 1953	38° 38′	73° 10′	190–200	9	6½–19	42·4
149	June 30, 1953	38° 37′	73° 12′	145–165	2	18½–21	46·4
147	June 30, 1953	38° 36′	73° 14′	95–100	10	8–21	51·4
146	June 29, 1953	38° 33′	73° 18′	63–65	10	7–13	54
131	June 28, 1953	38° 13′	73° 40′	145–160	1	19	45·2
137	June 28, 1953	38° 10′	73° 45′	72–73	9	9–16	54·5
140	June 29, 1953	37° 38′	74° 14′	230–265	1	13½	41·4
139	June 29, 1953	37° 38′	74° 15′	120–130	2	15½	46·4

*From tip of rostrum to end of tail.

†On the three cruises made in 1953, from June 26 to July 29, and for the several hauls made July 8, 1954, temperatures were obtained for most of the hauls with a maximum-minimum thermometer attached to an otterboard. It may be presumed that these minimum temperatures, in most cases at least, were those prevailing at or very close to the bottom, at about deepest part of haul.

**In the 6 hauls made July 8, 1954, by *Atlantis* the 210 lobsters caught fell in the following size groups : 79 were 7 to 8¾ in. ; 97 were 9 to 12 in. ; 29 were 12¼ to 15 in. and 5 were 15½ to 17½ in. measured from end of rostrum to end of tail. In the 6 hauls made September 2-3, 1956, by *Caryn*, the 89 lobsters caught fell in the following size groups : 51 were 6¼ to 8¾ in. ; 24 were 9 to 12 in. ; 11 were 12¼ to 15 in. and 3 were 15¼ to 19¼ in.

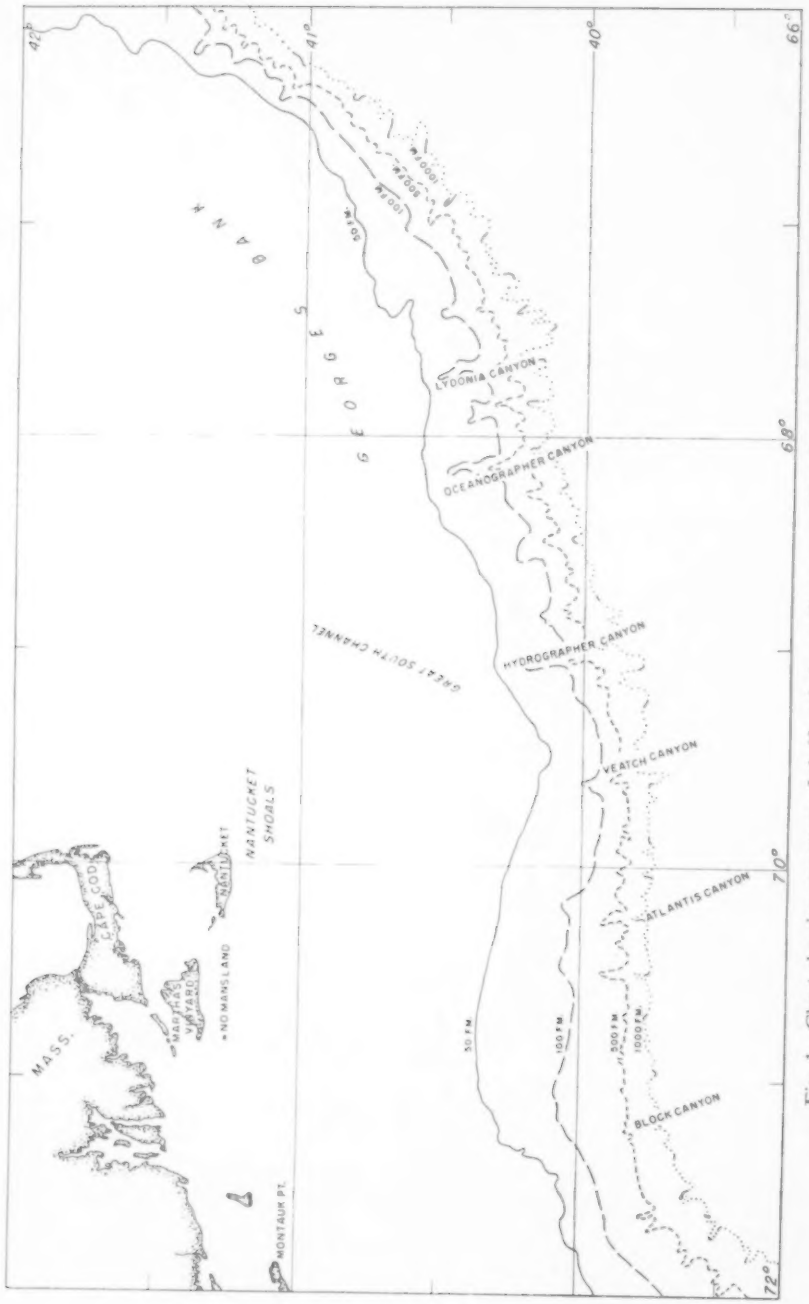

Fig. 1. Chart showing contours of shelf and slope off southern New England and Georges Bank.

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The area explored, although only about 5 to 20 miles wide, extends some 600 miles – or from the offing of La Have Bank to that of Cape Charles, Virginia, from long. 63° 17′ to 74° 15′W – and with few exceptions, the depths ranged from 70 to 730 fm (128-1340 m). Of the 217 hauls in which no apparent mishap to the gear occurred (including 15 made by *Atlantis* in 1954 and 9 by *Caryn* in 1956) 181 were deeper than 100 fm (183 m).

It should be emphasized that the purpose of our exploratory fishing was chiefly an attempt to determine the identity, distribution and relative abundance of the fishes living in this region. Therefore, lobster catches (Table 2) for the most part were incidental and the numbers taken would have been substantially greater if our efforts had been directed chiefly to seeking and exploring the most productive lobster grounds (SCHROEDER, 1955).

While several sizes of trawls were used, the hauls were too few in number to reveal any significant correlation between the width of foot-rope and the quantities of lobsters caught. Although the best catches were between depths of 70-100 fm (128-183 m), the number of lobsters taken deeper suggests that commercial fishing might also prove successful well beyond 100 fm (183 m). Such was the case, for, as a result of reports* released by the Woods Hole Oceanographic Institution, one trawler (*Sonia*) began fishing offshore for lobsters during the fall of 1953. The next year other boats joined in this fishery which has proven to be a successful one†.

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The *Delaware* has reported a number of substantial catches of lobsters, mostly large in size, along the southern slope of Georges Bank. Catches per trip ranging up to 7000 lb or more were taken between long. 66° 45′ and 67° 20′W and between 69° 10′ and 69° 30′W., chiefly in depths of 175-275 fm (320-503 m), during January and November 1955 and January, March and May 1956 on those cruises when lobsters were especially sought. Thus this is conclusive evidence that large numbers of lobsters are to be found in these depths at least as far eastward as the vicinity of Lydonia Canyon (Fig. 1).

There are but few records of sizable catches of lobsters taken offshore in winter, a season when the lobster trawlers either lay up their boats or find it more profitable to seek fish. Hence, it is of interest to report 800 lb of lobsters trawled in 55-65 fm (101-119 m) SSW from No Mans Land, landed by *Cap'n Bill II* February 3, 1956 along with a fare of fluke, and 400 lb in about 76 fm (139 m) from between Hydrographer and Oceanographer Canyons, landed February 29.

To the west and south of New England, landings of lobsters taken offshore with otter trawls have shown a steady increase in the New York-New Jersey region during the past few years. These catches, compared with those taken inshore with pots, are listed in Table 3.

New Jersey landings account for the greater part of the recent large increase in the otter-trawl catch (Table 3). Thus, for the years 1950 to 1956 these catches amounted to 28·2, 29·8, 36·0, 43·6, 53·0, 61·7 and 48·4 per cent, respectively, of the total catch landed in both New York and New Jersey taken by trawls and pots. The New York landings for the same years were 14·0, 15·9, 11·4, 7·1, 12·8, 9·8 and 17·7 per cent,

*Published in *Atlantic Fisherman*, September and October 1952 ; *Maine Coast Fisherman*, October 1952 ; *Boston Traveler*, December 1, 1952 ; *Boston Globe*, December 28, 1952, January 25, 1953 ; *New Bedford Standard Times*, January 18, 1953.

†An account of some of the trips is given in the Appendix, p. 279.

respectively. Thus, percentagewise, the New Jersey landings of trawl caught lobsters have been tending sharply upwards while those for New York have shown but little increase during this period.

In 1955, 14 otter-trawlers from New Jersey fished 4 to 5 months for lobsters and their catch represented about 75 per cent of the total poundage for that state, the remainder being taken with lobster and fish pots, while in 1956 there were 16 lobster trawlers operating from May to September. Some of the catches were made as deep as 100-250 fms (183-457 m) (E. A. LOVERDE, private communication).

*Table 3. Lobster catch landed in New York and New Jersey for certain years from 1929 to 1956**

Year	*Pots* (lb)	*Otter trawls* (lb)	*Total catch* (lb)	*Percentage of total catch taken by otter trawls*
1929	1,386,343	26,285	1,412,628	1·8
1930	1,544,370	2600	1,546,970	0·2
1931	1,125,443	12,038	1,137,481	1·0
1932	866,641	570	867,211	
1933	703,546	6470	710,016	0·9
1935	633,100	6200	639,300	1·0
1937	625,200	10,400	635,600	1·6
1938	543,200	28,100	571,300	5·0
1939	644,400	22,000	666,400	3·3
1940	560,200	32,800	593,000	5·6
1942	460,500	43,200	503,700	8·5
1943	704,100	64,100	768,200	8·3
1944	652,000	68,500	720,500	9·6
1945	408,800	46,900	455,700	10·3
1947	502,800	106,300	609,100	17·4
1948	503,300	255,400	758,700	33·6
1949	552,900	106,400	659,300	16·1
1950	367,500	267,800	635,300	42·2
1951	221,800	186,800	408,600	45·7
1952	371,200	335,200	706,400	47·4
1953	475,800	489,500	965,300	50·7
1954	354,450	680,900	1,035,350	65·8
1955	374,370	939,170	1,313,540	71·5
1956	448,740	874,820	1,323,560	66·1

*Based on annual reports of the U.S. Bureau of Fisheries published from 1931 to 1941, for the years 1929-1938, and the U.S. Fish and Wildlife Service published from 1942 to 1956 for the years 1939 to 1954. Statistics for 1955 and 1956 are based on data furnished by Mr. E. A. LoVerde and Mr. C. T. Smith, of the U.S. Fish and Wildlife Service.

Further south small amounts of lobsters are taken by otter-trawls along with catches of fish. Such catches as entered in the published statistics include, for Maryland, 100 to 1500 lb and, for Virginia, 300 to 10,500 lb per year for the period 1944-1953. The present known southerly range of this lobster is North Carolina.

The most northerly range of the American lobster, on the other hand, is the Strait of Belle Isle. At the northern extreme, large catches of lobsters are taken off the Maritime Provinces of Canada, Quebec and Newfoundland, the landed catch there for 1950 amounting to nearly 40 million lb*. Up to the present time, however, there is no otter-trawl lobster fishery in that region. Newfoundland trawlers fishing in moderately deep and deep water seldom catch a lobster. Dr. W. TEMPLEMAN†

*For an excellent account of the fishery and habits of the lobster in Canadian waters, see WILDER, (1954).

†Private communication.

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states that the *Investigator II* operating offshore all over the Newfoundland Banks and in deep water down to 400 fm (730 m), since 1946, has never caught a lobster. Furthermore, the only records which have come to his attention are :

No. of lobsters	*Locality*	*Depth* (fm)	(m)	*Date*	*Boat*
1 male, 3½ lb	46° 50′N, 57° 04′W (St. Pierre Bank)	90	165	20/3/54	*Gaultois*
1 female, 3½ lb	46° 46′N, 56° 22′W (W of Miquelon Is.)	30	55	16/1/55	*Gaultois*
1 female, total length 14 in.	6 miles off Cape Race	24–30	44–55	18/10/54	*Blue Spray*
1 female, 12$\frac{5}{16}$ in.	44° 00′N, 51° 40′W	43	79	7/5/57	

MIGRATIONS

Marking experiments indicate that lobsters, with few exceptions, do not make long migrations but tend to stay within a limited area, at least during the year or so that their marks can be recognized or their tags remain attached.

In the Magdalen area in the southern part of the Gulf of St. Lawrence (TEMPLEMAN, 1936, p. 43) the greatest distances travelled by tagged lobsters were only 5 or 6 miles in 9 to 11 months, while two tagged at Prince Edward Island were recaptured about 20 and 30 miles away, as measured along an uneven shore line. Thus, in both localities, the population as a whole appears to be more or less local in character with no definite migrations, but rather a scattering and wandering of some individuals.

" From favourable warm water areas (in the vicinity of Newfoundland) where many young survive, lobsters wander slowly during their lifetime of 20 years or more and come to occupy many areas around the coast unsuitable for the survival of the young and many miles distant from the point where they originally settled at the bottom. These are the first areas to be fished out, since once lobsters are caught it takes many years for other lobsters to wander in to take their places, migration being only on the average about 2 miles a year (according to our tagging investigations in St. George's Bay, 1938-39) " (TEMPLEMAN, 1941, p. 14).

Of about 100,000 lobsters tagged in Canadian waters in the past 25 years more than half were recaptured but only 3 of these had moved as much as 60 miles (WILDER, 1957 ; also 1950). From this and other evidence he concluded that the Canadian lobster population " is made up of a series of separate, independent stocks with very little mixing between areas " (WILDER, 1957, p. 7). Again, of a 1000 lobsters tagged for the Maine Department of Sea and Shore Fisheries at Monhegan, about 25 per cent were recaptured but only 9 were caught as far as 2 to 2½ miles from the place of liberation (HARRIMAN, 1957).

Offshore, in depths from about 100 to 275 fm (183-457 m) along the southern slope of Georges Bank and offing of Nantucket Shoals, about 2250 lobsters have been tagged* as a result of exploratory trawling by the U.S. Fish and Wildlife Research

*The tag, stamped with number and return address, was a stainless steel strip bent on one end to hook on the posterior edge of the carapace and fastened to the rostrum by a rubber band.

Vessel *Delaware* in co-operation with the Department of Natural Resources of the Commonwealth of Massachusetts :

Locality where tagged	*Date*	*No. tagged*	*No. recovered*	*Remarks*
15-30 miles E of Lydonia Canyon 67° 06′-67° 21′W	Nov. 1955	786	6*	3 nearby within few days 3 after 168-255 days, 12-25 miles N
App. 15-30 miles E of Lydonia Canyon	Jan. 1956	115	2	1 nearby 105 days later 1 after 166 days 40 miles to NE
E of Lydonia Canyon	May 1956	825	7	5 within 25-38 miles N 36-102 days later 2 within 12-23 miles W after 62-449 days
Veatch Canyon 69°14′-69° 25′W	Jan. 1956	350	7	All within 10 miles after 117-207 days
Veatch Canyon	May 1956	177	5	4 within 10 miles after 7-104 days 1 about 45 miles NE after 53 days

*In addition, a tag, but no lobster was found in the stomach of a cod taken on Nantucket Shoals in Nov. 1957, two years after the lobster was liberated.

Of the 27 recaptured (4 by the *Delaware*, 23 by fisherman), 15 were taken within a few miles of the tagging locality and 12 were more than 10 miles away. Of the latter, 9 had moved northward onto Georges Bank, a distance of about 11 to 40 miles and in depths of about 30 to 50 fm. One was taken about 45 miles to the north-east or about 60 miles south-east of Nantucket, in 38 fm. Two wandered to the west.

The paucity of recaptures from shoaler water on nearby Georges Bank, where many otter trawlers operate, indicates that relatively few of the offshore lobsters wander far from their deep water habitat, if it can be assumed that a substantial mortality and/or loss of tags* did not ensue soon after they were released. Nor is there any indication that many of them migrate or wander far to the west in either deep water (beyond 100 fm) or shoal, for none were reported west of Veatch Canyon, where, in addition to the many trawlers seeking fish, much of the commercial offshore otter trawling for lobsters occurs.

Experiences of fishermen trawling offshore have shown that an area yielding a good catch one week may be sparsely populated the next, but soon thereafter may again be productive. In such a case the poor fishing might be due to the large catches of the previous trip, but if so, certain areas, at least, soon become repopulated by lobsters which shift ground presumably from close by.

Thus far, no significant differences, either racial or subspecific, have been found

*Deep water lobsters, if uninjured, survive the ordeal of being hauled along in the trawl while fishing and being brought aboard from depths well beyond 100 fm, for a large percentage reach the market in lively condition. Hence, it is probable that the attachment of tags and the return of the lobsters to the sea bottom does not entail a heavy mortality. Presumably, relatively few tags are lost within the first six months or so by individuals which molt, for large lobsters are believed to shed their shells infrequently and many of those tagged ranged in weight from 5 to 7 or 8 lbs. Some were much larger. However, after the lapse of about a year the loss of the tags from this cause would become increasingly great.

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to separate the inshore from the offshore stocks of lobsters. Dr. FENNER A. CHACE, Jr. of the U.S. National Museum compared several lobsters taken beyond 100 fm with shoal water specimens and found no constant differences between the two. My comparison of several specimens taken in February 1958 near Veatch Canyon, in about 60 fm, with others from close inshore substantiate this. However, Dr. CHACE points out that a large series from the two regions should be compared. If it can be determined that the inshore and offshore populations differ racially this would give added weight to the present opinion that the two populations are for the most part distinct with relatively little intermigration.

While the offshore population comprises lobsters of all sizes, individuals of 2 lb or more make up a much larger percentage of the population than in inshore waters where the fishery has been intensive for many years. Lobsters are believed to grow to be very old but there appears to be no reliable data for estimating the maximum age. Individuals of 15 to 25 lb are not rare in offshore waters while the largest one recorded (WILDER, 1954, p. 5) weighed 45 lb. It is probable that these very large lobsters are more than 15 years of age and it seems logical that during such a life span some of them may wander many miles.

The early development of the lobster has long been known (HERRICK, 1896 ; 1911). The larvae have a free-swimming stage of one to two months before they settle to the bottom at a length of a little more than $\frac{1}{2}$ in. and " since larvae are hatched over wide areas, and since there is yet no practical way of marking them, it is extremely difficult to determine the direction, speed and extent of their surface drift " (WILDER, 1957, p. 24). Thus we have yet to determine the origin of the larvae which take to the bottom offshore and the destination of the larvae which hatch in deep water off our coast*.

THE DEEP-WATER RED CRAB, *Geryon quinquedens*

Off the east coast in deep water, there is a species of crab (*Geryon quinquedens*), which is very good to eat, reaches a fair size, up to 2 lb or a little more, with a large one yielding 4 ounces of meat. Although it soon dies if exposed to air or water temperatures much above about 45°F (7·2°C), it will stay alive for several days if buried in ice. As otter trawlers become equipped for fishing in greater depths, this species may some day become the source of a commercial fishery, if a market for the canned meat can be established.

This crab, first described (SMITH, 1879, p. 35) from a number of very small specimens taken off Casco Bay, Maine, and off Massachusetts Bay, in about 100-160 fm (183-292 m) was later taken by the *Albatross* between the offings of Martha's Vineyard and Chesapeake Bay in depths of 535-1043 fm (980-1906 m) (SMITH, 1886). The range of *quinquedens* extends from south of Halifax (lat. 42° 37′N) to South Carolina in 100-1000 fm (183-1828 m) (RATHBUN, 1929, p. 35) and possibly to Brazil in depths of 22-1178 fm (40-2153 m) (RATHBUN, 1937, pp. 266-270)†. More recently limits

*For a list of references on the biology of the lobster and on the lobster fishery, see DAWSON, (1954).

†Dr. FENNER A. CHACE (private communication) points out that Miss RATHBUN evidently included two species in her *quinquedens*, the other being *G. affinis*. The specimen figured by Miss RATHBUN as *quinquedens* is really *affinis* (CHACE, 1940, p. 39). The two species are alike in general appearance and grow to about the same size. Living or fresh specimens may be readily identified by colour : *quinquedens* is red or deep orange, *affinis* creamy buff. Anatomical differences are noted by CHACE (1940, p. 40).

G. affinis probably does not occur much north of the offing of Chesapeake Bay, but is widely distributed in the lower latitudes of the Atlantic and Indian Oceans.

given for *quinquedens* are from the offing of Nova Scotia (42° 46′N, 63° 22′W, *Cap'n Bill II* Sta 88) southward to at least the north coast of Cuba (CHACE, 1940, p. 38).

A brief account of the relative abundance of the red crab by depths and geographic areas, as a result of exploratory otter-trawling during 1952 and 1953, is given by SCHROEDER (1955, p. 371). Some of the figures in the latter report have been modified in the more detailed summary given in Table 4 which also includes 12 hauls made by the *Caryn* in 1948 and 1949.

Table 4. *Composite catch of deep water red crabs taken along the continental slope between the offings of Nova Scotia and of Virginia from* 1948 *to* 1953 *by the* Caryn *and the* Cap'n Bill II *arranged by depths and geographic areas. Egged females are not included*

	Area A		*Area B*		*Area C*		*Area D*	
	Long. 63° 17′-65° 59′W		*Long.* 66° 00′-69° 59′W		*Long.* 70° 00′-71° 59′W		*Long.* 72° 00′-74° 15′W	
Depth (fm)	*Number of hauls*	*Average no. of crabs per haul*	*Number of hauls*	*Average no. of crabs per haul*	*Number of hauls*	*Average no. of crabs per haul*	*Number of hauls*	*Average no. of crabs per haul*
50-100	1	0	10	0	2	0	7	1
101-150	0		5	0	7	0	6	3
151-200	0		2	1	8	2	3	126
201-250	2	0	7	35	11	29	2	210
251-300	8	16	4	79	4	12	3	245
301-350	12	49	3	38	5	50	1	68
351-400	6	26	4	45	2	80	4	118
401-450	6	23	5	12	6	80	2	69
451-500	6	52	11	11	2	29	2	60
501-550	4	115	1	5	1	34	2	14
551-600	0		1	33	0		2	22
601-650	1	18	1	2	0		2	14
651-730	1	30	0		1	9	2	6

†All of the catches were made in June and July excepting a few hauls by the *Caryn* in September. The quantities listed are adjusted to represent one hour's fishing of the net on bottom. Obviously the small mesh of the trawls used was not necessary to capture red crabs and it should be emphasized again that the nets were designed to explore the fish population and that crustaceans formed but an incidental part of the catch. Furthermore, the catches of red crabs would have totalled considerably more if trawling had always been concentrated in those areas where crabs were found in greatest abundance. The larger trawls yielded, on the average, more crabs than the smaller one, as was to be expected, but no attempt was made to compensate for these differences in evaluating the results in this table.

Red crabs were so generally distributed throughout the region explored that they were caught in all but 10 of the 140 hauls made deeper than 200 fm in Areas *A* to *C* and deeper than 150 fm in Area *D* (Table 4). The most productive region was found in Area *D* in depths of 150 to 400 fm, but deeper than this all Areas, *A* to *D*, appeared to have a crab population of about the same magnitude. In the 150-200 fm zone of Area *D* (between 38° 13′-38° 44′N, 73° 01′-73° 40′W), the 3 hauls made in late June 1953 and averaging 126 crabs (Table 4) yielded 176, 152 and 44, respectively.

On the basis of our present knowledge, no explanation can be offered as to why crabs were so scarce in the 150-200 fm zones of Areas *B* and *C* as compared with Area *D* or why the latter region was the most productive one down to about 400 fm. However, it is probable that crabs are more plentiful a little shoaler than 200 fm in Areas *B* and *C* than our records indicate for Capt. Warren Vincent, while trawling

lobsters to the east of Veatch Canyon (Area *B*) in the vicinity of 39° 55′N, 69° 20′W, took 12 to 20 red crabs per 1 hr tow in 175-200 fm during May 1956. He also took " many large red crabs " in 260 fm in Area *B* on his first lobster trawling trip (p. 281) in April 1957, where our exploratory trawling found the best average catch of red crabs. But Capt. Vincent and other otter trawl fishermen operating off southern New England seldom catch red crabs shoaler than this.

Most of the crabs taken can be classed as large and medium large, i.e., about 4 to 5½ in. across the widest part of the carapace, with a few reaching 6 in. The smaller ones were chiefly 3 to 4 in. in width, relatively few being less than this. Specimens with a 5½ in. carapace have a leg spread of about 23 in. In a small series of measurements, males averaged 1 in. wider in carapace than females. A male of 5 in. weighed 1 lb 7 oz. and one of 5⅝ in. weighed 2½ lb.

Males outnumbered females and in many of the hauls they comprised the entire catch. Thus, of 115 tows in which the sexes were recorded, 43 contained males only and in the others males were most often in the majority (Table 5).

Table 5. Average number per haul of male, female, and egged female red crabs taken shoaler and deeper than 400 fm *between lat.* 42° 46′ *and lat.* 37° 38′N.

	Shoaler than 400 fm				*Deeper than* 400 fm			
	Number of hauls	*Males*	*Females*	*Egged*	*Number of hauls*	*Males*	*Females*	*Egged*
Area *A* Long. 63° 17′-65° 59′W	21	30	9	1	18	41	10	5
Area *B* Long. 66° 00′-69° 59′W	16	38	8	3	10	19	4	0
Area *C* Long. 70° 00′-71° 59′W	16	34	8	1	10	35	10	13
Area *D* Long. 72° 00′-74° 15′W	14	76	51	24	10	30	3	0

In individual tows with a large percentage of females (adjusted to one hour's fishing), there were :

No. of tows	*Area*	*Depth zone* (fm)	*Males*	*Total females*	*Females with eggs*
1	*D*	201-250	226	219	99
2	*D*	351-400	64	226	156
1	*C*	401-450	33	141	117
1	*A*	501-550	75	65	26

These were exceptional, especially in the relatively large number of egged crabs taken, for in many hauls, none of the females carried eggs, although the hauls were all made during June and July.

The majority of the hauls, deeper than about 200 fm, throughout the areas explored, were made on muddy bottom, which was seldom of a consistency to clog the fine meshed nets. Although red crabs were relatively plentiful on this bottom, good catches were also taken on hard bottom. One haul in particular, which con-

tained many stones, yielded 156 crabs averaging about 30 to a bushel (42° 36′N, 64° 15′W).

Bottom temperatures varied little, deeper than 200 fm :

Area	*Depth* (fm)	*Temperature*	*Depth* (fm)	*Temperature*
A	201-250	40·5 (4·7)	701-730	38·0 (3·3)
B	201-250	41·3 (5·2)	701-730	39·0 (3·9)
C	201-250	42·0 (5·5)	701-730	38·5 (3·6)
D	201-250	42·4 (5·8)	701-730	38·8 (3·8)

Thus, temperature *per se* does not appear to afford an explanation of the variations in abundance of crabs that might exist within a given depth zone (see SCHROEDER, 1955, p. 372).

Acknowledgements—Thanks are due to the captains of several otter trawlers for their co-operation in furnishing information of their experiences in the offshore lobster fishery, among them ALBERT DAHL, RUSSELL GRINNELL, JARED VINCENT and, especially, the late WARREN VINCENT* who made available records of his daily catches and other pertinent data ; to A. W. ANDERSON, D. L. HOY, E. A. LOVERDE, C. T. SMITH, R. A. SOULEN and J. L. SQUIRE, Jr., of the U.S. Fish and Wildlife Service for the most recent catch records and other useful information ; to CHARLES L. WHEELER and RICHARD W. BURTON of the Department of Natural Resources of the Commonwealth of Massachusetts for records of lobsters tagged offshore ; to Dr. FENNER A. CHACE, Jr., of the U.S. National Museum for comparing inshore and offshore lobsters for possible racial differences and for data on the deep-sea red crab ; to Dr. D. G. WILDER of the St. Andrews, N. B., Canada, Biological Station for data on tagging and migrations of lobsters in Canadian waters and to Dr. W. TEMPLEMAN for records of deep water catches off Newfoundland.

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*Capt. Warren Vincent was lost at sea in July 1958, when his boat was sunk in a collision.

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APPENDIX

As no detailed report has been published on the methods employed, or the catches made, by the offshore lobster fleet operating off our coast, the accounts furnished through the kindness of several of the otter trawler captains, namely, Albert Dahl of the *Sonia*, Russell Grinnell of the *Metacomet*, Jared L. Vincent of the *Priscilla V* and the late Warren Vincent of the *R. W. Griffin, Jr.* follow :

Sonia. The *Sonia* is a 60 ft dragger, usually fishing with a crew of 4. In 1954, she was equipped with 3 storage containers on deck (two of them 3 ft wide, 2½ ft deep, 12 ft long, each holding about 1600 lb of lobsters ; one 3 ft. × 2 ft × 7 ft holding about 800 lb, or a total of 4000 lb), supplied with running water from two pumps (2 in. and 3 in.). When these were filled, lobsters were packed in the hold on burlap and ice. The trawls used by Capt. Dahl had a 98 ft head rope, 105 ft sweep rope, of 4 in. mesh 24 or 30 thread throughout, boards weighing about 500 lb each and with 340 fm of $\frac{9}{16}$ in. wire on the winch.

Capt. Dahl made 7 trips up to the middle of July in 1954 and returned to New Bedford after each of these with 3500 to 5000 lb of lobsters, or a total of 30,000 lb. An average catch per haul of about 1½ hr was 7-8 bushels in 60-80 fm and 5 bushels in 120-130 fm. Other trips the summer of 1954 were reported by Capt Dahl as follows :

" Left New Bedford July 15 ; arrived back in port, 6 p.m., July 17. Fished in area around 40° 04′N, 70° 34′–70° 37′W, chiefly in 77 fm. Caught 6000 lb of lobsters (excluding shorts, molting, damaged and egged lobsters) in 34 hr fishing ; first haul of 2½ hr took 20 bushels ; after that caught 14-16 bushels per 1¾ hr haul. Average weight of lobsters about 2 lb. of which 75 per cent were 3 lb or less, 25 per cent of more than 3 lb but with very few extra large. Short lobsters comprised about 10 per cent by weight of the total catch on the trip ; only 1 out of 30 or so lobsters was egged.

" Arrived on the same ground as on previous trip on the afternoon of July 19. Found but few lobsters and moved eastward to area around Veatch Canyon, 69° 51′ to 69° 54′W, in 80-100 fm. Here only 7 lobsters were caught in a 2 hr drag. Returned to the original ground, vicinity of 70° 34′W, and took 10 bushels in 2½ hr drag first haul. Fished 1½ days on this ground and caught 4500 lb of marketable lobsters, of which about 400 lb died enroute to port.

" Left port, July 25. Arrived on grounds noon July 26. Fished until 6 p.m., July 28. Arrived New Bedford early July 29 for Thursday market. Running time about 11 hr each way. Fished in vicinity of 40° 03′N, 70° 39′W, 80-93 fm. Landed 3500 lb of lobsters in New Bedford. Two sets were negative, one because net fouled and one because sharks attacked cod end and much of the catch was lost. Hauls ran 6-7 bushels in 2½ hr drags."

On August 17, 1954, the *Sonia* landed 4000 lb of lobsters, taken in 48 hr dragging in about 100 fm to the south of No Mans Land. Many " shedders " were returned to the water. The following

trip August 22 to the same area, but fishing somewhat deeper, 120-125 fm in rough seas, 3000 lb were landed. Proportionately fewer "shedders" were taken than in the 100 fm area.

Early in July 1955, Capt. Dahl caught 8200 lb of lobsters to the south of No Mans Land in 70-77 fm. At that time 8 draggers were otter trawling for lobsters off southern New England, 1 each from Cape May and Pt. Pleasant, New Jersey, one from Greenport, Long Island, 3 from New Bedford and 1 each from Woods Hole, Massachusetts and Portland, Maine.

Metacomet. About 5000 lb of lobsters were landed on August 15, 1954 taken in the vicinity of 39° 58′N, 69° 25′W, in about 62 fm using a trawl with a 120 ft sweep and 103 ft head-rope of 4 in. stretched mesh. Another trip, of 3500 lb was landed on October 4, 1954.

On June 9, 1955, Capt. Grinnell, at sea 4 days, landed 5080 lb of lobsters at Woods Hole, after fishing in about 75 fm, 15 miles west of Block Canyon (about 71° 20′W) and on June 19, 7000 lb were brought in from the vicinity of 70° 35′W, a little farther to the east. On this trip only one soft lobster was caught and very few egg-bearers.

Priscilla V. Two trips the last week of July 1954 to an area fished earlier that month by the *R. W. Griffin, Jr.* resulted in landings of 3000 and 2500 lb after trawling for 2 days and a night in each case. One-hour drags during the day and 1 to 1½ hr at night yielded no significant difference in catch per unit of effort.

Trawling in 85-86 fm to the south of Martha's Vineyard, August 14-15, 1954, in 22 hauls of about 1 hr each, the following estimated numbers and weights of saleable lobsters were taken : 1580 of 1-3 lb (3160 lb) and 150 over 3 lb (840 lb) or a total of 4000 lb. In addition, 1070 lobsters (weight not given) were soft and 900 shorts. In much the same locality, August 18-19, 1954, in 13 hauls of about 1½ hr each, 510 lobsters of 1 to 3 lb (1020 lb) and 100 over 3 lb (550 lb), or a total of 1570 lb was taken in 36 hr fishing. Also caught were 355 soft and 365 short lobsters which were released. Egged lobsters caught on these trips were not recorded.

Early in June, after trawling near Block Canyon in about 75 fm, 7700 lb were landed.

R. W. Griffin, Jr. A catch of 2800 lb of marketable lobsters obtained in the immediate vicinity of the position trawled experimentally (40° 02′N, 70° 35′W, 77 fm) by the Woods Hole Oceanographic Institution on July 8 was landed in Woods Hole, July 12, 1954, after 18 hr dragging. Most were 1-3 lb, a few were very large, but many short lobsters were thrown back.

Twenty-six drags in 44 fm in the vicinity of 40° 18′N, 69° 20′W, yielded 5200 lb of lobsters landed on October 21, 1954.

Capt. Warren Vincent kindly made available his daily records for 1955, 1956 and 1957 (Tables 6-8). "Selects" were lobsters of marketable size up to 4 lb, "large" over 4 lb in weight and "culls" were of various sizes but lacked one or both claws or were otherwise imperfect but saleable. The lobsters were kept alive below decks in tanks with running water.

During 1955 most of the catches (Table 6) were made in the vicinity of Veatch Canyon and to the south of No Mans Land in 55-90 fm, chiefly in 60-80 fm. No records are available as to the number of short, soft or egged lobsters.

During 1956 trawling was chiefly south of No Mans Land and in the vicinity of Veatch Canyon, as in 1955, but some fishing was done to the east between Lydonia and Oceanographer Canyons. On the first two trips in May, catches were made in 165-210 fm (vicinity of Veatch Canyon and to the south of No Mans Land) with fair success (Table 7) when lobsters were scarce in the usual 70-80 fm areas. By the end of May and for the rest of the season, they were taken in shoaler depths (60-80 fm). On September 7-9, however, to the south of No Mans Land, about 800-1000 lb a day were caught in 50 fm or a little more than on September 11-12 in 74-82 fm further offshore. The largest 24 hr catch during 1955-1956, on May 29-30, 1956, was 4480 lb of saleable lobsters.

Although Capt. Vincent made random notes when the proportion of non-saleable lobsters was unusually large, no methodical record was kept of short lobsters, "eggers" or "shedders" in 1956, but many were taken and returned to the water. Thus, in the period; July 22-25, trawling south of No Mans Land in 70-80 fm, in addition to about 4200 lb of saleable lobsters, about 1500 shorts and many soft lobsters and a few eggers were caught. On the July 31-August 5 trip in 58-64 fm near Veatch Canyon, about 500 lb of shorts (probably about 800 individuals) were taken and released in addition to 8070 lb of saleable lobsters landed. On August 27 only about 600 lb of saleable lobsters were caught and nearly ⅓ the total catch were shorts and ⅓ eggers.

During the spring of 1957 Capt. Warren Vincent resumed offshore trawling for lobsters (Table 8).

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Table 6. *Total lobster catch per trip of the* R. W. Griffin, Jr. *taken off southern New England during* 1955

Days fished	lb *selects*	lb *large*	lb *culls*	lb *total*
June 13-16	2985	3990	430	7405
24-28	4400	4300	700	9400
July 4-8	5730	2640	930	9300
25-29	4880	2530	830	8240
Aug. 5-7	4190	3310	935	8435
24-30	3580	4000	1050	8630
Sept. 5-10	2450	3430	590	6470
23-28	3900	1790	1290	6980
Grand total	32,115	25,990	6755	64,860
Percentage	50	40	10	

Table 7. *Lobster catch per trip of the* R. W. Griffin, Jr. *taken off southern New England during* 1956

Days fished	lb *selects*	lb *large*	lb *culls*	lb *total*
May 6-10	2230	3000	370	5600
18-21	2870	3555	675	7100
27-30	2440	7785	475	10,700
June 5-11	2930	6130	440	9500
June 27-July 1	3930	3170	600	7700
July 6-12	4410	3110	680	8200
19-25	3590	3390	610	7590
July 31-Aug. 5	3800	3440	830	8070
Aug. 12-16	1340	1660	240	3240
23-27	720	810	190	1720
Sept. 7-12	1430	3150	320	4900
Grand total	29,690	39,200	5430	74,320
Percentage	40	52	8	

Table 8. *Lobster catch per trip of the* R. W. Griffin, Jr. *taken off southern New England and on Georges Bank during* 1957

Days fished	*Trip No.*	lb *selects*	lb *large*	lb *culls*	lb *total*
Apr. 20-25	1	1750	5995	290	8035
May 1-5	2	4130	5720	550	10,400
9-14	3	5105	5770	830	11,705
18-20	4	1575	2350	345	4270
23-30	5	3535	6230	610	10,375
June 5-9	6	1140	1950	170	3260
July 2-7	7	4720	2480	580	7780
11-18	8	2280	2240	235	4755
July 25-Aug. 1	9	860	4315	40	5215
Aug. 13-19	10	440	7685	—	8125
25-31	11	45	1435	—	1480
Grand total		25,580	46,170	3650	75,400
Percentage		34	61	5	

Following are notes concerning the 11 trips made during 1957.

Trip no.	*Vicinity of*	*Depths fished* (fm)	*No. of tows*	*fishing* (hr)	*Remarks*
1	Veatch Canyon	175-260	37	120	about 900 egged and 300 short lobsters
2	Block Canyon	165-300	34	96	at least 1500 egged lobsters (2-15 lb) and about 400 short
3	Block Canyon	160-250	44	120	many egged, few short lobsters
4	Block Canyon	170-270		44	no data on egged or short lobsters
5	Block Canyon	160-300	50	168	about 20 egged, 10 short lobsters per tow (100 egged to State Hatchery)
6	Block Canyon NE Atlantis Canyon	120-175 80-200		48 38	short trip, engine trouble
7	NE Atlantis Canyon	70-80		114	no egged lobsters, about 50 shorts per tow
8	Veatch Canyon NE Atlantis Canyon Block Canyon	55-80 75 50		84 48 48	no egged lobsters, 30-50 shorts per tow
9	Veatch Canyon	42-75		48	some short and egged lobsters
	South Central Georges Bank	30-68		110	no short lobsters, egged females present
10	South Central Georges Bank	29-32		136	large number soft lobsters, no shorts
11	South Central Georges Bank (3 days) Veatch Canyon (4 days)				saleable lobsters scarce. Many small ones a few egged females near Veatch Canyon

Capt. Vincent on July 27 (Trip 9) shifted from Veatch Canyon to south-central Georges Bank on the telephoned advice of a flounder dragger who happened upon a good lobster ground. In the next 5 days he took 4140 lb of lobsters, mostly large, in 29-32 fm, chiefly within an area of about 2-4 miles^2 in an isolated pocket of mud bottom surrounded by an extensive expanse of hard bottom. On the following trip, he landed 8125 lb from the same locality. These catches are of interest, because the regular fleet fishing on Georges Bank in depths of 50-60 fm or so has usually found lobsters to be few in number and scattered. Although this concentration cannot be explained, the locality may merely not have been intensively trawled for a long time, the lobsters may have gathered to mate and some may have wandered in from deeper water. Possibly the character of the bottom may be a factor. Offshore particularly beyond about 60 fms, good catches are made on both hard and soft bottom. This is in contrast to inshore waters, where plentiful catches are taken on hard, especially rocky bottom.

On the final trip (No. 11) in 1957, three days in this same area of Georges Bank, visited only a week earlier, yielded a catch notably smaller, possibly because the population had dispersed or, more likely, because it was decimated on the two previous trips.

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Reflexion studies in the eastern equatorial Pacific

GEORGE G. SHOR, JR.

(*Received* 28 *October* 1958)

Abstract--A limited seismic reflexion survey has been made in a portion of the equatorial Pacific far from land and shielded from turbidity-current deposition. It covers the boundary between present-day clay deposition in the north and present-day carbonate deposition in the south. The profiles show that the sediment is decidedly thicker in the carbonate area and provide evidence for a greater rate of accumulation in valleys than on hills.

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INTRODUCTION

IN November 1954, the research vessel *Spencer F. Baird* occupied a series of closely spaced coring stations in the area near 125°W, 3½° to 13½°N. While the coring was being done, reflexion shots were fired whenever they would not interfere with other operations. The results of this admittedly limited survey are presented here, together with a few tentative conclusions about marine sedimentation derived therefrom.

This is an area of low hills, approximately 4500 m below sea level, with a few small seamounts. It lies along the boundary of clay and calcium carbonate deposition (see Fig. 1) and is remote from land sediment sources. It has been referred to as the " Eupelagic Area " by ARRHENIUS (1952) who has suggested that this area is probably one of purely pelagic sedimentation free of turbidity-current deposition from land sources. He has reported high rates of sedimentation in the carbonate zone. A determination of variation of sediment thickness across the border of the calcareous area may serve to tell whether this local high rate of deposition has existed in the past.

The Clipperton Fracture Zone crosses the area, possibly coincidentally, at the northern margin of the calcareous area. The average sea-depth changes across the fracture zone and is about 200 m shoaler on the south side. Detailed bathymetry is given by MENARD and FISHER (1958).

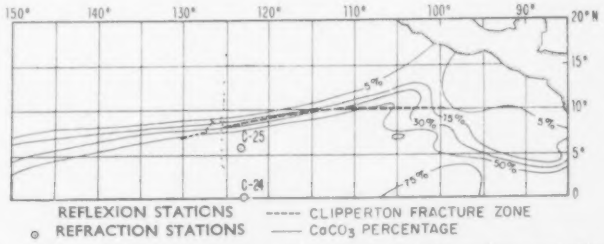

Fig. 1. Location of stations with respect to calcium carbonate boundary and Clipperton Fracture Zone. Modified from ARRHENIUS (1952).

FIELD PROCEDURE

The locations of the reflexion shots were controlled by the needs of the coring programme. Locations were along two generally north-south lines about 200 km apart (Fig.1) with close spacing on either side of the carbonate boundary and wider

spacing farther away. In a few locations a detailed bathymetric survey was made to establish a base map, and attempts were made to place cores and shots specifically over hilltops and valley floors. Two or more reflexion shots were fired on each station.

Shots were half-pound tetryl blocks, fired with time fuses at a depth of about 45 m. From one to four hydrophones were streamed at depths between 30 and 60 m. Sub-bottom reflexions were distinguished from side echoes by recording on multiple frequency bands and picking only those low-frequency arrivals which were unaccompanied by high-frequency returns.

SEISMIC RESULTS

A sample record is shown in Fig. 2. In this record, the first to fourth multiple reflexions from the basement were received; they are indicated by the events marked B_1, B_2, B_3, and B_4. The events marked S_1, S_2, S_3, and S_4 are the reflexions from the

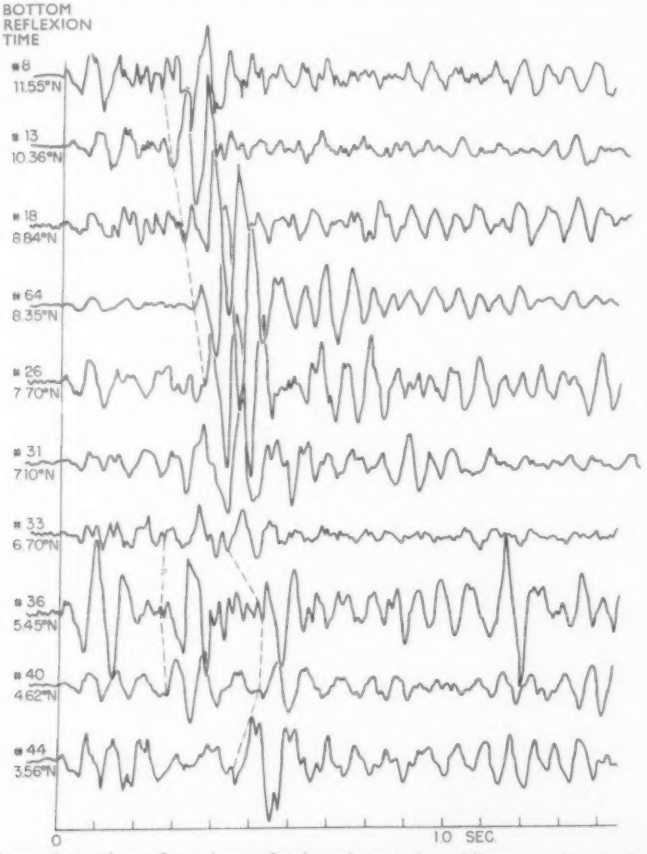

Fig. 3. North-south section of tracings of selected records. Alignment is on time of the first bottom reflexion.

upper surface of the sediment. They are distinguishable only for the first two multiples on the high-frequency traces; the travel times for the third and fourth arrivals were computed. These sub-bottom reflexions correspond to type "N" reflexions of HERSEY and EWING (1949) as do most of the records obtained in this area. A few type

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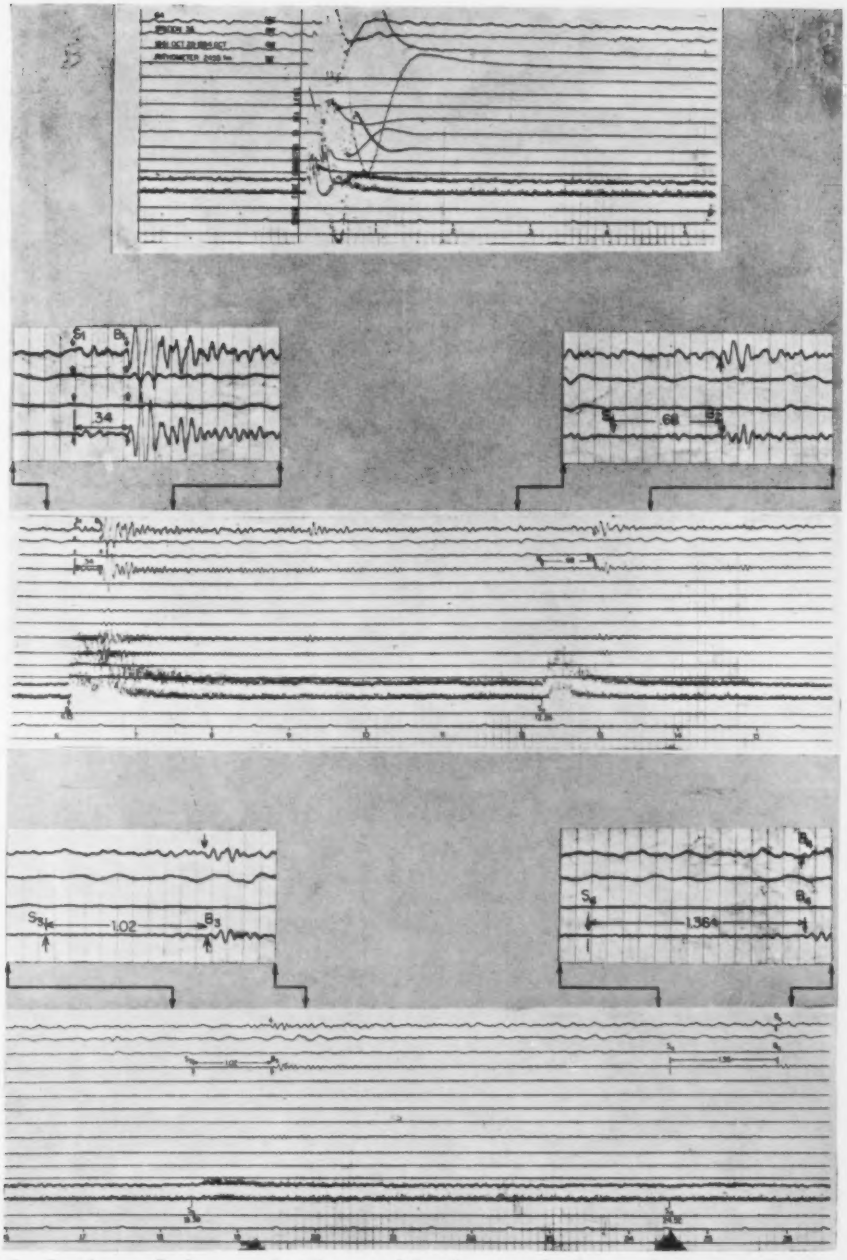

Fig. 2. Specimen reflexion record. The record has been cut in three and the upper four traces enlarged in four places. These four traces are low-frequency channels from four different hydrophones; the fourth trace has opposite polarity to the first three. Direction of first motion is shown by arrows. Traces 9 and 10 are band-pass; 13 and 14 are rectified high frequency.

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" R " reflexions also occur. It will be noted that there is variation in polarity in the four hydrophones on the low-frequency traces: the first three have positive pressure down; the fourth, positive pressure up. The polarity of the first motion reverses with successive reflexions because of the reversal at each reflexion from the ocean surface.

Two groups of reflexions were found on the records. A set of tracings of one low-frequency trace from each of ten records, arranged from north to south, is shown in Fig. 3. The records are aligned on the time of the bottom reflexion. On this set can be seen one consistent arrival in the northern records; it appears to deepen to the south and on shots 36 and 40, it is preceded by an earlier arrival. Similar arrivals are found on the remaining records of the survey. In Fig. 4 are shown five records

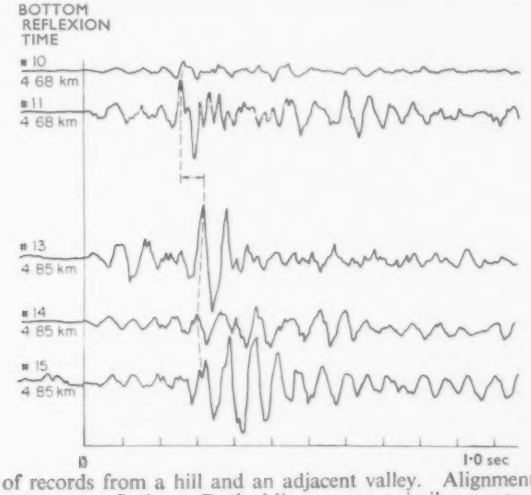

Fig. 4. Comparison of records from a hill and an adjacent valley. Alignment is in time of the first bottom reflexion. Dashed lines connect similar events.

taken within a small area, showing variation with topography. Again, the records are aligned on the bottom reflexion time rather than the firing time so as to show variations of sediment thickness. Records 10 and 11 were taken over a small hill; records 13, 14, and 15 over an adjacent valley. It can be seen that the valley shots have the basement reflexion arriving about 0·05 sec later than the shots on the hill, indicating thicker sediment in the valley.

These record profiles suggest that there is a variation of sediment thickness both from north to south and from hill to valley; in order to separate these effects without additional adjacent hill-valley combinations, it has been necessary to resort to statistics.

The records were timed by correlation of similar phases, and an attempt was made to pick the true beginning of the sub-bottom arrival. This is admittedly a subjective process, and there can be some difference in the times picked by different observers or by the same observer on different occasions. It is believed that the picks are at least consistent; they are plotted in Fig. 5.

A statistical fit has been made for linear variation of bottom-to-basement reflexion time interval as a function of latitude and water depth for the deeper (and more consistent) reflexion. The " plane of best fit " is expressed by the equation

$$t = 0{\cdot}33 - 0{\cdot}034L + 0{\cdot}21Z \pm 0{\cdot}04 \text{ sec} \qquad (1)$$

where

t = time from the sea-floor reflexion to the " basement " reflexion

L = variation of latitude from the mean (8·26°N)

Z = variation of sea-depth from the mean (4·562 km.)

The equation is, of course, applicable only over the zone of observations. It indicates that there is about 20 per cent more relief at the base of the sediment than at the top and a thinning of about 10 per cent of the mean for each degree of north latitude. The partial correlation coefficients are 0·89 for the latitude term; 0·48 for the depth

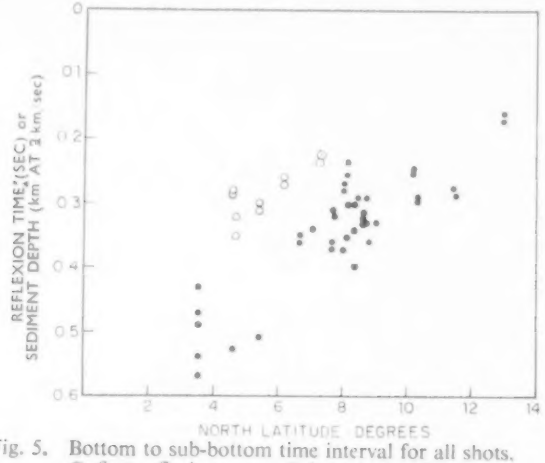

Fig. 5. Bottom to sub-bottom time interval for all shots.
⊙ first reflexion ● basement reflexion

term. If the separation of the reflexions into two groups is justifiable, there is a significant correlation of sediment thickness variation with both latitude and water depth. Even if the two groups of reflexions are combined for statistical analysis, the latitude term is still significant, although the significance of the depth term becomes marginal.

The absolute sea-depth has been used above because it is amenable to statistical handling. Of greater geologic significance is a correlation with topographic position, if the cause of thickness variation is topographic control of the rate of accumulation. Five shots were located over hilltops; 14 over valley bottoms. Reflexion times, corrected for the latitudinal variation by the second term of equation (1) have means differing by 0·05 sec for the two groups; the difference of the means is significant at the 98 per cent confidence level.

The results of this analysis have been used to make the plot of Fig. 6 where the statistically determined term for variation with water depth has been removed, and the reflexion times have been plotted as a function of latitude alone. The straight line in the plot is the line of regression for latitudinal variation. If a velocity of 2 km/sec for the sediment is assumed, the plot may be considered a composite profile of sediment thickness in kilometres.

On the *Capricorn Expedition* strong reflexions were obtained at refraction stations C24 and C25, east of the reflexion profile (RAITT, 1956, and private communications).

At these stations the reflexion shots were fired at varying ranges out to the distance at which the refracted waves begin, making it possible to obtain velocities for the material above the reflecting horizon by $X^2 : T^2$ analysis. On station C24, the sediment velocity was 2·6 km/sec, and the depth obtained from reflexion and refraction data agreed closely. On station C25, the velocity in the material above the reflecting horizon was 2·1 km/sec, but the depths from reflexion and refraction disagreed. The reflexion was from a horizon well above the " basement " layer which produced the refracted arrival. When an adjustment is made for depth variation relative to the average of the lines of shooting using the factor in equation (1), the reflexion on C25 coincides closely with the shallow horizon of the reflexion lines, and the refraction

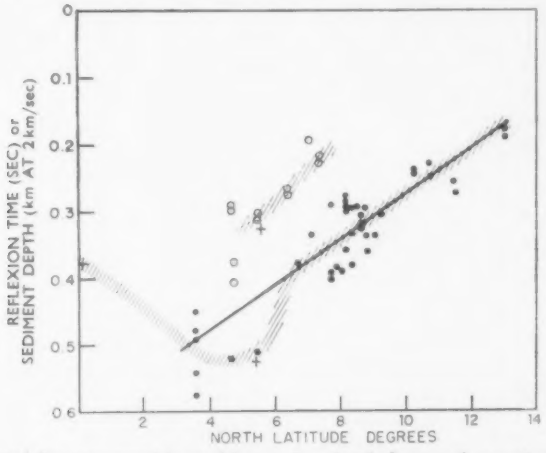

Fig. 6. Data adjusted for topographic position, using depth factor of equation (1); statistical fit entered as straight line, best curve also drawn. Stations from RAITT (1956) entered with topographic adjustment made.

○ first reflexion ● basement reflexion + data from RAITT (1956)

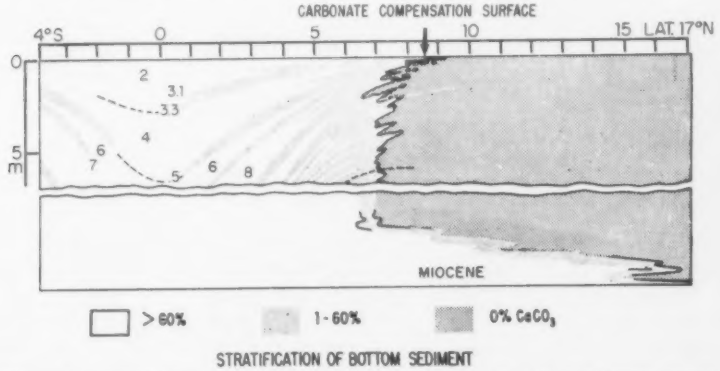

Fig. 7. Sediment composition and stratigraphic correlation in the shallower material, from ARRHENIUS (1958).

arrival coincides with the deeper horizon. The data from these two stations have been entered on Fig. 6, and curves fitting the combined data appear as dashed lines. A similar section presented by ARRHENIUS (1958) for the first 15 m of sediment using

evidence from core analysis is reproduced in Fig. 7 for comparison. The similarity is striking.

On Figs. 2, 3, and 4, the difference between the reflexion coefficients at the sea floor and the base of the sediments is very large. Such contrast is to a lesser extent true of the entire area studied and is the reason usable reflexion data can be obtained with relatively unsophisticated methods. Average low-frequency reflexion coefficients were determined from those records which showed multiple reflexions; they were 0·3 for the water-sediment interface and 0·7 for the deeper reflexions. There was no significant difference between the coefficients for the arrivals from the base of the sediments and from the horizon within the sedimentary section. These reflexion coefficients are compatable with the velocities near 2 km/sec for the sediments and 5 km/sec for the basement determined by other methods. They imply that the best explanation for the reflexion from within the sedimentary section is that it comes from material with density and velocity close to that of the " basement " that is too thin and discontinuous to appear as a refracted wave.

GEOLOGICAL SIGNIFICANCE

The thickened sediment found in the valleys could arise from several causes. Turbidity-current deposition from distant sources could produce this effect; it is believed, however, (ARRHENIUS, 1952) that the area is completely shielded from these. A much more probable cause is local movement of material from hills to valleys by current action or solifluction. The report of Tertiary sediments outcropping or covered by a thin stratum of Pleistocene-Recent material on topographic highs in this area (ARRHENIUS, op. cit.) is added evidence.

The thickening of the sediment occurs near the boundary of the zone of high carbonate deposition as described by ARRHENIUS (1952) and shown in Fig. 1 and Fig. 7. This implies that the conditions now prevailing have existed for some time in the past. Extrapolation of rates of accumulation of oceanic sediment is dubious at best, but using rates given by ARRHENIUS for recent sedimentation in this area, one can at least say that high carbonate deposition in the southern part of the area has existed for some tens of millions of years. This thickening of the sedimentary section to the south is entirely sufficient to account for the shoaler average ocean depth south of the Clipperton Fracture Zone; the implication is that in this area the shoaling is a result of carbonate deposition rather than the reverse.

Acknowledgement—This work was supported by the Bureau of Ships and the Office of Naval Research under contracts with the University of California. MAX SILVERMAN fired the charges, ALAN JONES prepared the equipment, GLORIA SLACK and WANDA WILSON aided in some of the computation, EDWARD GOLDBERG and GUSTAF ARRHENIUS gave much helpful discussion of the problems. RUSSELL W. RAITT provided the results of the *Capricorn Expedition* work and has aided in the project throughout.

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Contract NObsr 72512 *and Nonr* 2216(05).
Contribution from the Scripps Institution of Oceanography, New Series.

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Bathymetry of the Gibbs Hill area, Bermuda

JOHN NORTHROP, MAURICE BLAIK and ROBERTO FRASSETTO

(*Received* 15 *September* 1958)

Abstract—Precision depth recordings were made South of Gibbs Hill, Bermuda, along a number of closely spaced sounding tracks. The accuracy of transit navigation and the sounding coverage were considered sufficient to justify correcting the soundings for both sound velocity and slope. The corrected soundings show that a steep sided submarine spur extends south-south-east from the shelf break off Gibbs Hill. The spur has a topographic relief of 300 fm and is about 3 miles long and ½ mile wide. At the 1000 fm curve, the feature broadens into a platform that extends another 12 miles seaward to the 2000 fm curve. True slopes along the steep portion of the spur are as high as 50 and the bottom echoes appear to be from a number of highlights causing "crescents" on the record. Where a definite break in slope occurs, the apparent bottom shown on the bathygram is that of a diffraction pattern from an edge and all points on this crescent migrate to a point, which is the true position of the break in slope.

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INTRODUCTION

SLOPE migrations are usually not made in routine bathymetric surveys because the navigator is primarily interested in the sonic sounding, not the corrected depth (SHALOWITZ, 1930 ; ADAMS, 1942). In areas where true depth is needed to complete oceanographic work, corrections in addition to those for true sounding velocity are usually not made because the navigational error is often larger than the slope migration would be (KOCZY, 1956). However, for nearshore areas where excellent navigation control is assured by either transit readings or radio (Decca, Raydist, Loran) exact depths can be obtained on sloping bottoms where such information is needed.

Slope corrections used by cartographers for marine surveys sometimes follow the general procedure outlined by SHALOWITZ (1930). This correction technique is unsatisfactory, however, because it assumes that the slope is known and is substituted into the basic equation

$$h = \frac{e}{\cos \phi}$$

where h is the true depth under the vessel, e is the echo distance read from the depth recorder, and ϕ is the slope of the bottom.

In the present work, the true slope is not assumed to be known, but is calculated from the apparent slope by the equation

$$\sin a = \tan a'$$

where a is the true slope and a' the apparent slope (see Appendix). From this relationship, it can be seen that the true slope is always steeper than the apparent slope. For example, in determining the correct bottom topography, an apparent slope of 45° migrates to a true slope of 90°, or a vertical cliff. The magnitude of this error was recognized by DE BLAVOUS (1930, 1931) and PINKE (1938) who discussed the migration technique in great detail.

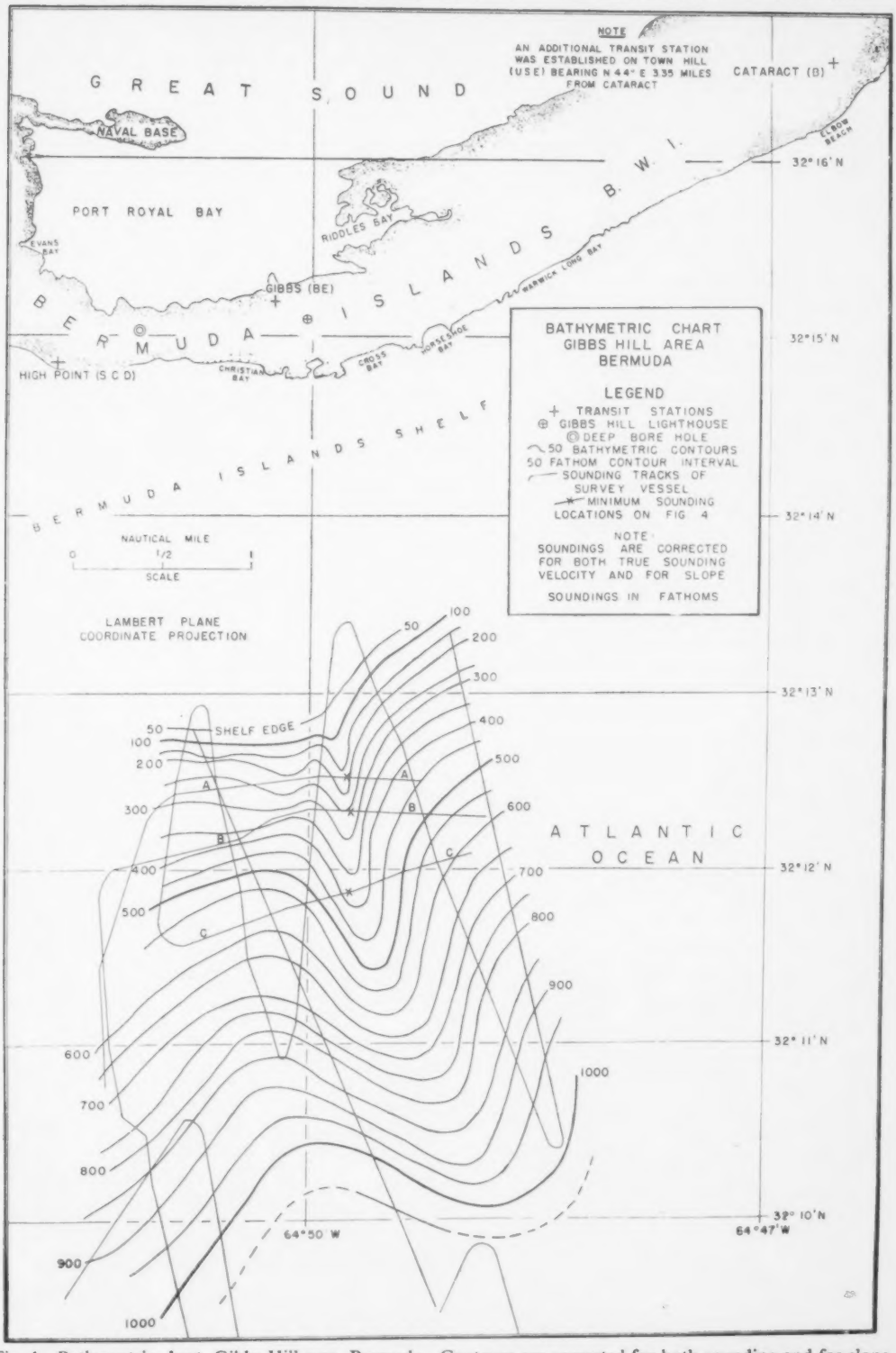

Fig. 1. Bathymetric chart, Gibbs Hill area, Bermuda. Contours are corrected for both sounding and for slope.

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In all of these methods it is assumed that the correction is for major elements in the bottom slope, because the minor undulations are effectively masked by the "scanning" effect of the echo sounder which receives all echoes from within its subtended cone of sound. The later returns are masked by the first and if several bottom highlights are crossed, their diffraction pattern "crescents" overlap (KNOTT and HERSEY, 1957 ; LUSKIN, *et al.*, 1957 ; HOFFMAN, 1957).

METHOD

A series of crossing sounding tracks, never more than $\frac{1}{2}$ mile apart, was made by the survey ship (Fig. 1). The soundings were measured with a continuously recording precision depth recorder (LUSKIN, *et al.*, 1954) using Times facsimile Models RJC and RD92A/UX with an Edo echo sounder (Model AN/UQN-1b). Navigational control was provided by three onshore transit stations used in pairs to take bearings of the survey vessel's mast every 2 minutes. The navigational error was thereby reduced to a minimum.

The soundings were vertically plotted for every two-minute position (ship's speed was 5 knots) and a provisional contour chart was drawn using 100 fm contours. The soundings were then corrected for true sounding velocity (DEL GROSSO, 1952). The slope migration was applied to a one-to-one vertical profile drawn normal to the regional trend of the contours. Apparent slope angles of the bottom were measured on this profile.

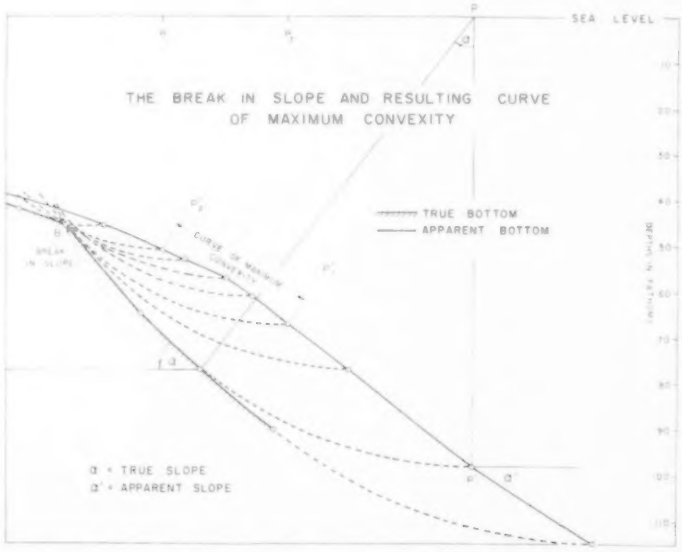

Fig. 3. Slope Migration. Part of echo sounder trace (Fig. 2) has been migrated upslope. Apparent slope at P' migrates to true slope at α. The apparent bottom, curve of maximum convexity, between points P_1' and P_2' all migrate to B, the break in slope.

Assuming constant sound velocity (see Appendix), the tangent of the apparent slope equals the sine of the true slope (DE BLAVOUS, 1930). Vertical and horizontal migrations were as follows (see Appendix) :

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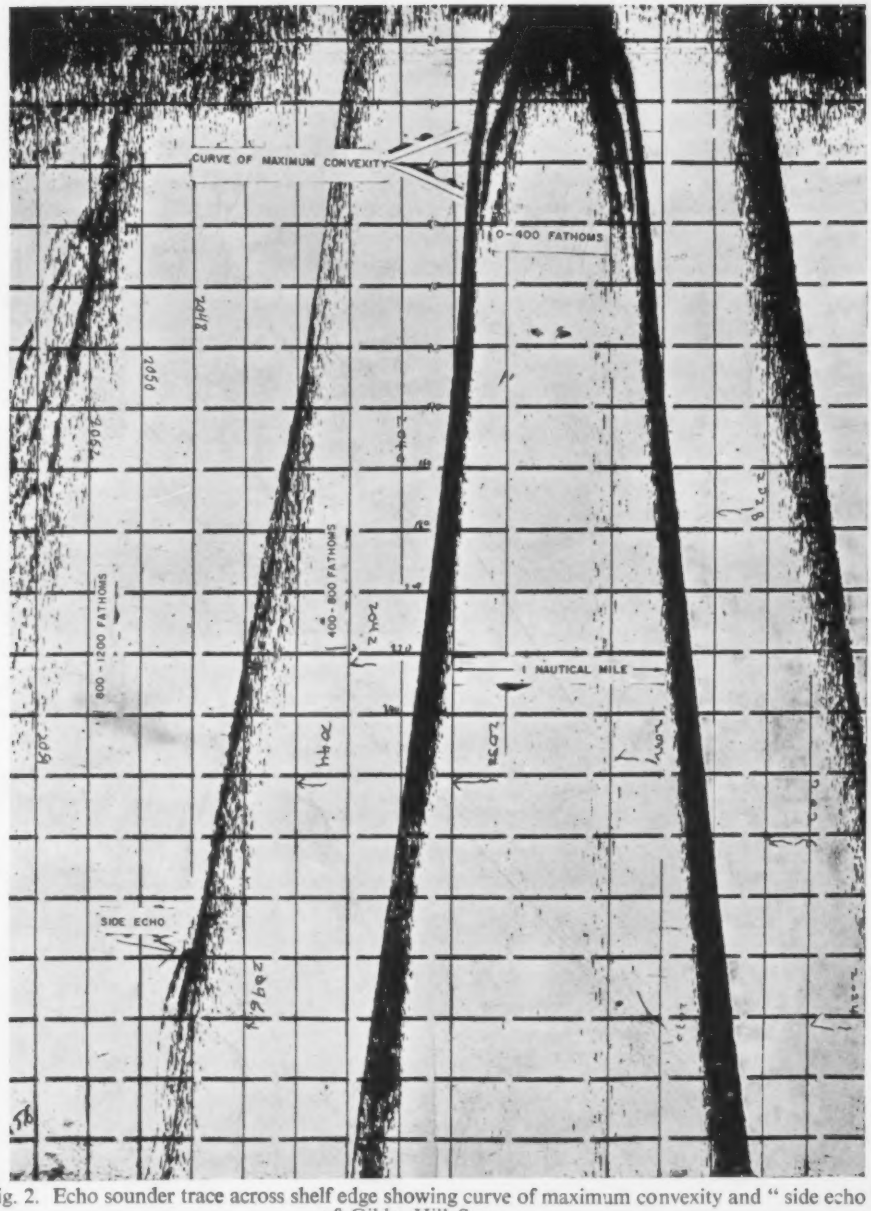

Fig. 2. Echo sounder trace across shelf edge showing curve of maximum convexity and " side echo " of Gibbs Hill Spur.

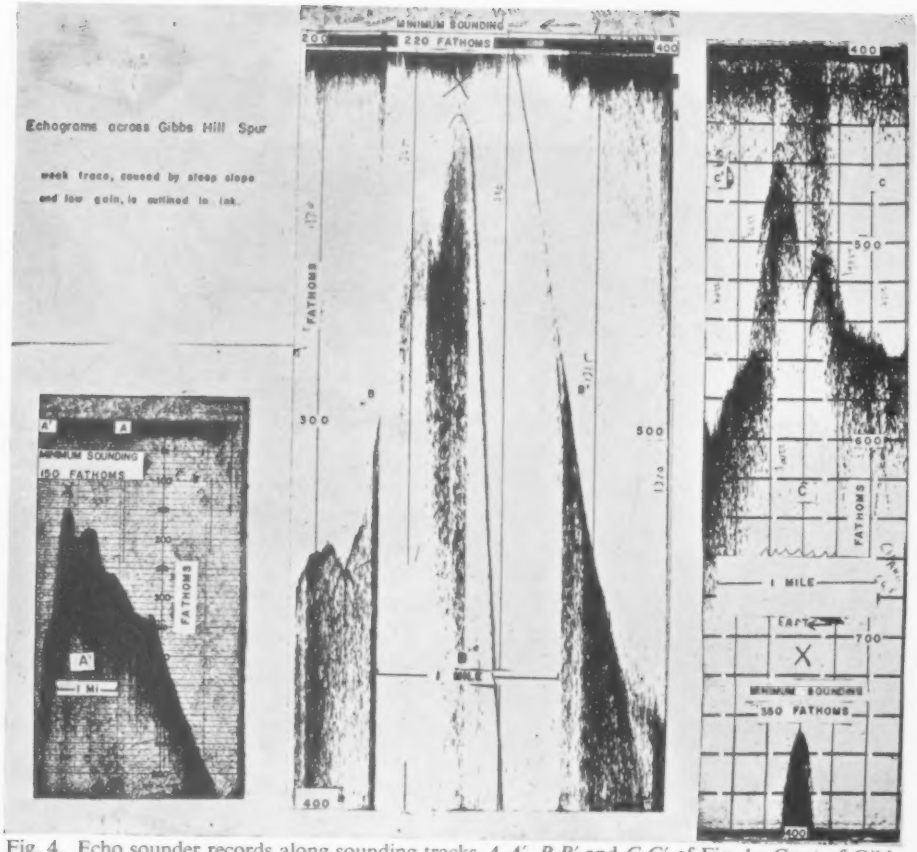

Fig. 4. Echo sounder records along sounding tracks *A-A'*, *B-B'* and *C-C'* of Fig. 1. Crest of Gibbs Hill Spur is marked *X* on each crossing. Depths in fathoms, distance in nautical miles.

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$$\Delta z = z_a (1 - \cos \alpha)$$

$$\Delta x = z_a (\sin \alpha)$$

where α is the true dip and z_a is the apparent depth (sonic sounding).

If desired, the migrations can be plotted graphically by swinging an arc of radius PP′ up slope through α (Fig. 3). Its intersection with the extended true dip angle α from *P* will be the true dip determination on a one-to-one scale.

In determining the true position of the break in slope, a part of the fathometer record (Fig. 2) between the island shelf and slope has been likened to a "curve of maximum convexity" after HAGEDOORN (1954). The curve of maximum convexity is the locus of vertically plotted points for diffraction (SOMMERFELD, 1897; HAGEDOORN, 1954) from the point where the break in slope occurs. When migrated, all points on the curve of maximum convexity will intersect at point *B* (Fig. 3) and short line segments will cluster around *B*. Point *B* is therefore the break in slope, and within the limits of P_1' and P_2' (Fig. 3) the vertically plotted reflexion times will migrate to their true position and meet at *B*.

BATHYMETRY

The Gibbs Hill Spur has a somewhat sinuous crest line that extends south-south-east from Gibbs Hill Lighthouse (Fig. 1). The feature does not appear on the island shelf, where it is probably overlain by the Pleistocene calcareous eolianites and limestones which extend to 245 ft below sea level in the bore hole west of Gibbs Hill (PIRSSON, 1914). At the 100 fm curve, the crest of the spur becomes well-defined and continues down to at least a 1000 fm. The crest slopes at a surprisingly uniform rate of 30° with the horizontal, and its sides slope at an average of 40° with local steepening up to 50°. The steepest slopes were recorded on the crossings shown on Fig. 4.

The crest of the spur (marked *X* on Fig. 4a) and a secondary, or lower, peak are shown on the shallowest crossing (*A*-*A*′ Fig. 1). The depression between the two peaks appears to be a canyon head but with the 60° sound beam used, it was not possible to get its true depth because the echo returns are from the walls. A quarter mile further south (*B*-*B*′ Fig. 1) another crossing was made with an expanded scale recorder. Again in this crossing the crest of the spur (*X* in Fig. 4b) stands out from the flanking shelf echoes and possible canyon head. Half a mile further south the crest was crossed again (*C*-*C*′ Fig. 1). This time a clear record was obtained (Fig. 4c) without interfering echoes from the now distant shelf. The slopes indicated within the measured mile, however, all cluster at the minimum depth point when migrated. This means that the apparent bottom trace shown within the marked mile on Fig. 4 (c) consists of the curve of maximum convexity caused by diffraction from the crest of the spur.

Farther south the crest of the spur was not obtained by axis crossings, but did show up as a distinct "side echo" on the bordering traverses (Fig. 2) from which it was possible to fix the location of the crest (HOFFMAN, 1957).

All the bathygrams show a high percentage of "crescents" or "cross-overs." Each highlight on the bottom is similar to a diffracting edge (SOMMERFELD, 1897) giving rise to a crescent. The envelope of a series of crescents, therefore, has been compared to the profile of an irregular bottom feature.

DISCUSSION

The use of high resolution echo sounders, accurate shore based navigation and closely spaced soundings have made it possible to determine the true bottom configuration of a heretofore unknown feature out to the 1000 fm curve. South of the limit of the detailed survey, the Gibbs Hill Spur was crossed by several additional traverses and appears to continue out to at least 2000 fm. At this depth it is a broad bank described by WOOLLARD (1952) as a possible location of lava outpourings from a separate volcanic pipe. (U.S. Navy Hydro. chart No. 5723 shows a pronounced topographic shoaling in the 2500 fm contour in this area and this has been substantiated by recent soundings on file at the Hydrographic Office).

The steep slopes associated with the Gibbs Hill Spur suggest that it may have been formed by lava outpourings from an auxiliary volcanic pipe, of which several are known in Bermuda. Magnetic and gravity studies (WOOLLARD, 1952) indicate that the major volcanic pipe in the Bermuda Islands lies under Port Royal Sound and that its radius is 2½ miles. Such a fissure erupting predominantly basaltic lavas (PIRSSON, 1914) may have had a number of secondary vents. Both Challenger and Plantaganet Banks to the south-west and Bowditch Seapeak (NORTHROP and FROSCH, 1954) to the north-east may be the loci of volcanic pipes from which lavas were extruded to form the present topography. The age of the volcanism has been estimated as Triassic by both PIRSSON (1914) and OFFICER *et al.* (1952). Others (MOORE and MOORE, 1946) prefer Late Tertiary. Triassic dating is supported by the appearance of Eocene and Miocene microfossils in the weathered layer of marine sediments and volcanics at depths from 245-455 ft below sea level in the well west of Gibbs Hill (PIRSSON, 1914 ; CARMAN, 1933 ; OFFICER, *et al.*, 1952). This sedimentary cover may have been eroded away (possibly by landslides or turbidity currents) from the Gibbs Hill Spur and deposited in depressions south-east of Bermuda (OFFICER, *et al.*, 1952) leaving the stark outline of the original volcanics characteristic of the Bermuda Rise topography (LUSKIN, *et al.*, 1954). Indeed, coring attempts in the area resulted in empty and bent coring tubes, which indicate a hard rock bottom (B. C. HEEZEN, private communication). The probably very thin or possibly absent sedimentary cover over the Gibbs Hill Spur accounts for the steep slopes and rough topography encountered during the survey. The use of high resolution echo sounder records and precise navigation has made it possible to map the true shape of ocean bottom features and this approach is considered a powerful aid in geological interpretation of submarine topography.

Acknowledgements—This work was done under a contract between Columbia University and the Office of Naval Research. The use of a radio, theodolite and T-boat of the Bermuda SOFAR station was kindly provided through the courtesy of G. R. HAMILTON ; preliminary soundings and advice were provided by B. C. HEEZEN. The authors are indebted to all the personnel of Hudson Laboratories who helped in the field work, and to the Captains of the survey ships, Lt. E. M. LEVEY, U.S.N.R., and WILLIAM ADAMS, their officers and men.

Hudson Laboratories
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Contribution from Hudson Laboratories No. 25.

APPENDIX

The vertical distribution of sound velocity was obtained from bathythermograph lowerings and

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Atlantis hydrographic station No. 1468, and is shown in Fig. 5 (a). Ray tracings for slopes up to 35° and depths to 1400 fm revealed negligible deviation from straight rays. Therefore, straight ray calculations are used in the following discussion.

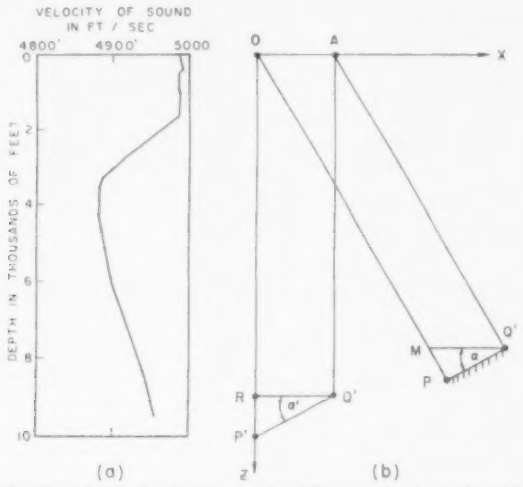

Fig. 5. Vertical distribution of sound velocity obtained from *Atlantis* station 1468 (a). Echo sounding ray diagram over sloping bottom for constant sound velocity distribution (b).

Assuming that there are no side echoes, one can proceed to derive a simple formula for the slope correction and migration of apparent bottom echo points to their real position. In Fig. 5 (b), a straight segment of recorded bottom is represented by line $P'Q'$ having a slope angle α', where the depths OP' and AQ' are the echo-soundings at O and A respectively. The soundings actually represent the section of the bottom shown by the segment PQ having a slope angle α. From triangles $P'Q'R$ and PQM, respectively, it is seen that

$$\tan \alpha' = \frac{RP'}{RQ'} = \frac{OP' - AQ'}{OA}$$

and

$$\sin \alpha = \frac{MP}{MQ} = \frac{OP - AQ}{OA}.$$

But $OP' - AQ' = \frac{V\Delta T}{2} = OP - AQ$, where ΔT is the travel time difference between the echoes received at O and A, and V is sound velocity in the ocean. Therefore, we see that (Koczy, 1956)

$$\sin \alpha = \tan \alpha'.$$

To find the true position of point P' (or any other point on the segment $P'Q'$) we define the vertical migration as

$$\Delta z = OP' - OP' \cos \alpha = OP' (1 - \cos \alpha) = z_a (1 - \cos \alpha)$$

recalling that OP and OP' must be equal.
In a similar way, we can specify the horizontal migration,

$$\Delta x = OP' \sin \alpha = z_a \sin \alpha$$

where z_a is the apparent depth of the echo point.

In correcting for slopes it should be realized that the profile must be migrated normal to the slope and that the beginning of the echo is assumed to be from a small section of the bottom nearest the ship and not necessarily directly below it. Specular reflexion is assumed and normal incidence

results from the small source-detector spacing. Therefore, slopes greater than the half-beam angle (30° in the present case) can be received because of transmission beyond the normally effective beam angle, roll and pitch of the ship, and irregularities in the surface of the bottom (HERDMAN, 1955). Theoretically, a plane slope greater than the semi-beam angle cannot be recorded, but as HERDMAN (1955) points out, this does not constitute a practical limit. In fact, the real limit is an apparent slope of 45° because in converting slopes of this order of magnitude to true slopes the vertical is approached. The fact that true slopes greater than the semi-beam angle were recorded may be explained by the specular reflexion at many small irregularities which can be present within the effective width of the base of the 60° sound cone. When a 12 kc/s frequency is used, a feature as small as a wave length (5") in this case) within range can produce a specular reflexion.

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The 18° water in the Sargasso Sea

L. V. WORTHINGTON

(*Received* 5 *January* 1959)

Abstract—The surface waters of the northern Sargasso Sea cool to a temperature of about 18 C each winter, forming an isothermal layer more than 350 m deep. This layer is also isohaline at 36·5‰. Much water with these characteristics is converged in this area and flows off to the south at the 300 m level. The excess of "18° water" formed each winter immediately south of the Gulf Stream can be clearly detected throughout the Sargasso Sea, at least as far south as the 20th parallel North. Some of the implications of this are discussed.

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INTRODUCTION

IT has long been known that in the northern Sargasso Sea a deep, well mixed layer is found during the winter months (ISELIN, 1936). This layer reaches its greatest depth (about 400 m) in early March when the whole water column above that depth is nearly isothermal and isohaline. Below this depth is found the main thermocline, which lies between 500 and 1200 m.

During the spring and summer a seasonal thermocline develops but the identity of the winter surface layer is never entirely destroyed : it persists throughout the year as a nearly isothermal/isohaline layer between the bottom of the seasonal thermocline and the top of the main thermocline until it is renewed at the end of the following winter. Even in late autumn there is still a pronounced inflexion at the 300 m level and at no time is the thickness of the nearly isothermal layer less than about 250 m in the northern (N of 32°N) Sargasso Sea. The temperature and salinity of this layer are remarkably constant. At the inflexion point which always occurs close to 300 m depth, the temperature is 17·9° ± 0·3°C and the salinity 36·50‰ ± 0·10‰. For convenience water of these characteristics can be called "18° water."

The 18° water is of more than usual interest because it is found in super-abundance far to the south of its area of formation, in places where the winter surface temperature minimum is far higher than 18°, and there is no possibility of its having been formed locally. Consequently excessive amounts of this water must be formed in the late winter in the area immediately south of the Gulf Stream, converge and spread out over the main thermocline (which represents an impenetrable density layer) in a manner reminiscent of bottom water formation in high latitudes. If the Sargasso Sea were only 400 m deep oceanographers would have no difficulty in describing what had occurred ; it would be clear that bottom water had been formed at the northern end of the sea in late winter and had flowed off to the south along the bottom. In view of the current interest in the problems of bottom water formation this 18° water assumes a special importance in that it might be possible by means of rapid and systematic measurements during one winter to estimate quantitively the various cooling effects necessary to converge and sink large amounts of surface water.

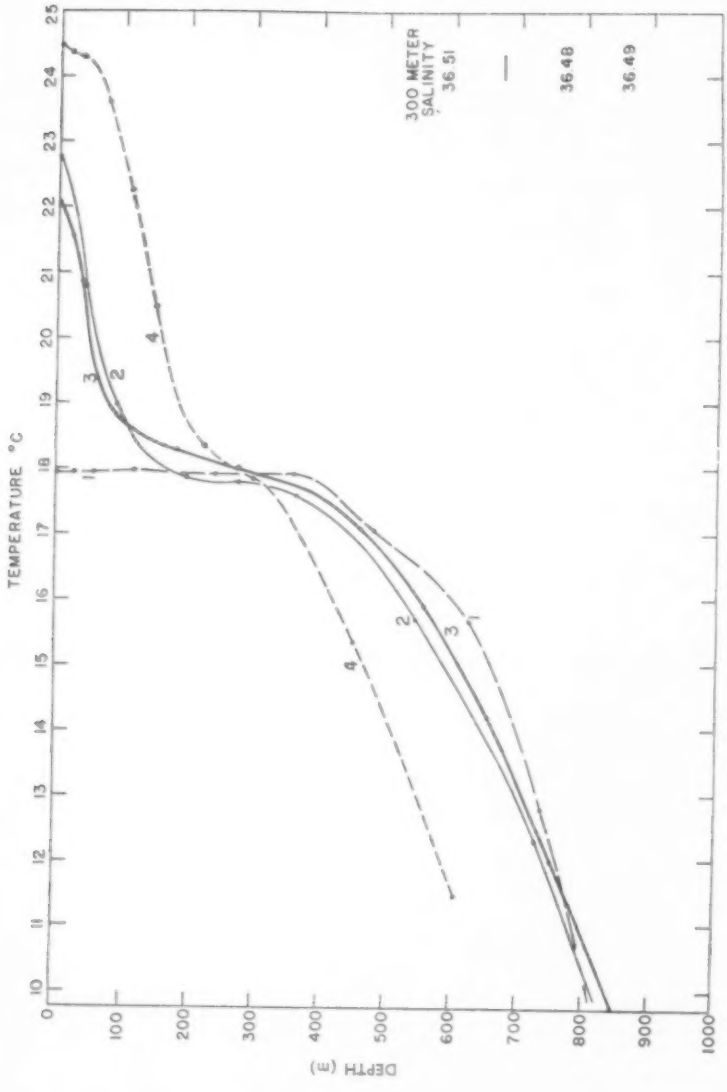

Fig. 1. Temperature-depth curves in the Sargasso Sea.
1 *Atlantis* 1153, 28 Feb, 1932 34° 02′ N 54° 05′ W
2 *Challenger* 53, 26 May, 1873 36° 30′ N 63° 40′ W
3 *Atlantis* 5306, 11 June, 1955 34° 53′ N 70° 16′ W
4 *Atlantis* 1483, 4 March, 1933 21° 46′ N 62° 48′ W.

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THE FORMATION OF THE 18°C WATER

The northern limit of 18° water is the Gulf Stream which transports surface water of 20°C or warmer at all seasons and whose surface salinity is 36·1‰ (ISELIN, 1936, 1940). The southern limit can be approximately delimited by means of BÖHNECKE's (1936) atlas, which shows winter minimum surface temperatures of 19° in lat. 33°. It is thus unlikely that any 18° water is formed to the south of Bermuda, at lat. 32°. The western limit of the formative area is again the Gulf Stream and the eastern limit, though ill-defined, is in the neighbourhood of 45°, or approximately over the Mid-Atlantic Ridge.

The formation of this water has been observed on three occasions ; at one station in the eastern portion (Table 1, Fig. 1) of the formative area and at two consecutive stations in the western portion.

Table 1

Atlantis 1153, 34° 02′N 54° 05′W, 28 *February* 1932

Depth	*Temp.* °C	*Sal.* ‰	O_2 *ml/l*
0	17·94	36·55*	5·08
30	17·92	36·51	5·02
61	17·92	36·50	4·97
122	17·96	36·50	5·05
183	17·91	36·50	5·00
242	17·91	36·51	5·00
363	17·90	36·51	5·01
484	17·04	36·35	4·53
628	15·65	36·08	4·19

On the eastern portion, the water is for all normal purposes isothermal, isohaline and of equal oxygen down to 363 m (Table 1). The two stations in the western portion of the area (*Atlantis* 4170, 34° 17′N 69° 26′W, 3 March 1941 and *Atlantis* 4171, 35° 18′N 68° 24′W, 4 March 1941) were both isothermal at 17·84°C (± 0·04°C), the former to a depth of at least 284 m and the latter to at least 297 m.† Both were isohaline at 36·50‰ ± 0·02‰ to these depths.

These are the only hydrographic stations which show deep, winter mixing of 18° water but there are vast numbers of bathythermograms from the whole length of the northern Sargasso Sea which show isothermal water at about 18° to at least 450 ft (137 m) and a lesser number to at least 900 ft (274 m) in late winter. These slides cannot be used for an adequate study of yearly variations in the supply of 18° water because, unfortunately, 274 m is about 100 m short of the bottom of the mixed layer.

Examples of vertical temperature curves from various points in the Sargasso Sea are shown in Fig. 1. Curve 1 is from the late winter station which has been tabulated above, illustrating the 18° water at its time of formation. Curves 2 and 3 are from the northern Sargasso Sea in spring, showing the extent of the seasonal temperature gradient at that season. *Challenger* station 53 (Curve 2) was included to show the remarkable consistency of the temperature at the inflexion in point of time. Curve 4

* The salinity value is probably high because a bucket was used instead of a Nansen bottle.

† The bottles on all these stations were spaced at about 100 m intervals so the isothermal layer was almost certainly deeper in each case.

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is from the southern Sargasso Sea where the 18° water is barely detectible. The 300 m temperature and salinity at this station (17·86°C, 36·49‰) remain the same as in the northern Sargasso Sea.

THE DISTRIBUTION OF THE 18° WATER

WYVILLE-THOMSON (1877, pp. 286, 287) was the first to remark on the overabundance of 18° water which he encountered at *Challenger* station 28, in lat. 24° 39′ long. 65° 25′. He was sufficiently impressed by its anomalous appearance at the station that he took

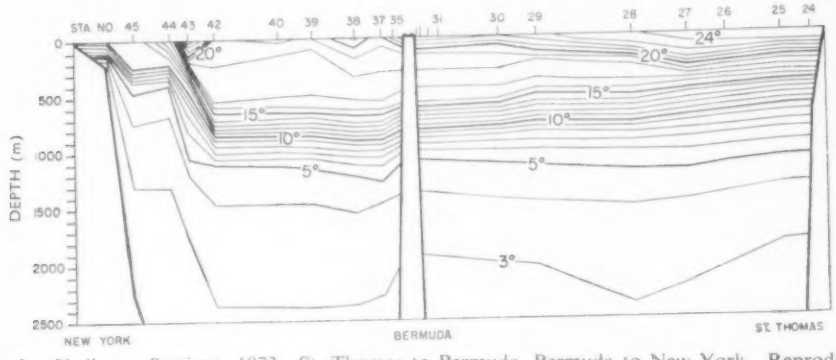

Fig. 2. *Challenger* Sections, 1873. St. Thomas to Bermuda, Bermuda to New York. Reproduced from WYVILLE-THOMSON (1877).

an extra series of measurements to confirm its existence. *Challenger's* sections from New York to Bermuda to St. Thomas are reproduced for historical interest and because they illustrate the southward penetration of this water very clearly (Fig. 2).

Water of northern Sargasso origin is found at the 300 m level throughout the Sargasso Sea. It can be recognized by either its temperature (usually a fraction of a degree below 18°) or by its salinity which lies close to 36·50‰. A chart of salinity at 300 m has been prepared from station data in the files at Woods Hole (Fig. 3). The black squares delimit the area in which 18° water is found. The eastern boundary is the least well-defined but east of lat. 40° no further water of north Sargasso origin is encountered. A surprising amount enters the Caribbean Sea, presumably through the Windward Passage, but while the squares in question are marked black they are borderline cases very close to 36·40‰. The high salinity values near 24°N 70°W are probably erroneous. The stations in question were made by the author in January 1947 : no postwar salinity data from Woods Hole can be relied upon until April of that year.

Further error would have been introduced if many of the U.S. Hydrographic Office stations had not been eliminated, since their salinity values appear to have had a higher scatter than was acceptable for this work. For evidence of this a histogram of salinity variation in the Bermuda area is reproduced through the courtesy of F. C. Fuglister (Fig. 4). The standard deviation from the mean T/S curve for Hydrographic Office data is ± 0·08‰ to ± 0·09‰ while all other sources up to 1954 yield a standard deviation of ± 0·03‰. Apart from these exceptions this 300 m salinity chart represents a good physical description of the extent of the Sargasso Sea.

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Fig. 3. Salinity at 300 m.
Black squares – 36·40‰ to 36·60‰ only
Numbered squares – 36·00‰ to 36·39‰ and
36·61‰ to 36·99‰
< for values below 36·00‰.

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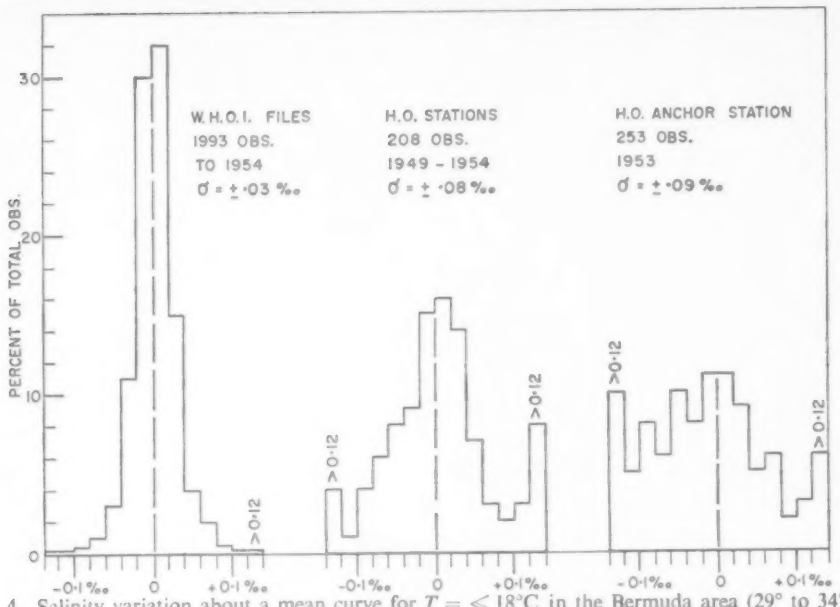

Fig. 4. Salinity variation about a mean curve for $T = \leqslant 18°C$ in the Bermuda area (29° to 34°N, 60° to 69°W).

THE OXYGEN CYCLE

It can be seen from the temperature, salinity and oxygen values (Table 1) that the 18° water, during its formation in late winter, is a layer of homogeneous water which is overturned constantly. During the remainder of the year, after thermal stability has developed this water has no further access to the sea surface and its oxygen diminishes slowly due to biological demand.

RAKESTRAW and CARRITT (1948) made a study of the seasonal variations in the chemistry of sea-water at three stations on the Montauk-Bermuda section, which were repeatedly occupied during 1937-1938. Their oxygen values at 300 m at station "C" which lies within the area of formation (op. cit. Fig. 5) were as follows :

		ml/l	*Putative Age*
December	1937	4·55	9 months
April	1938	4·95	1 month
July	1938	4·75	4 months
September	1938	4.45	6 months

This suggests that the biological consumption of oxygen is of the order of 0·5 ml/l/year in the core of the 18° water.

Further south in the Sargasso Sea the 18° water is characterized by an inflexion in the oxygen curve, or, more frequently by a reversal of the downward oxygen trend at 300 m. At station 1483 (curve 4, Fig. 2) the oxygen at 225 m was 4·63 ml/l and at 301 m, 4·75 ml/l. Reversals of this nature, while small, are almost always found south of 33°N to about 20°N in the Sargasso Sea. Of 172 recent stations which lie in an area between 33°N and 20°N and between 50°W and the Florida Current, 117 show a reversal of the oxygen curve at or near 300 m. Forty-seven show an inflexion of the curve at that depth and in only 8 is the influence of the 18° water not

perceptible in the oxygen curve. The latter almost without exception lie in the extreme southern border of the area. These reversals which are not found elsewhere in the North Atlantic suggest that the water at 300 m is of more recent origin than that immediately above it. Since this higher oxygen layer is maintained despite a biological demand of 0·5 ml/l/year it should follow that the convergence of 18° water is active during most winters.

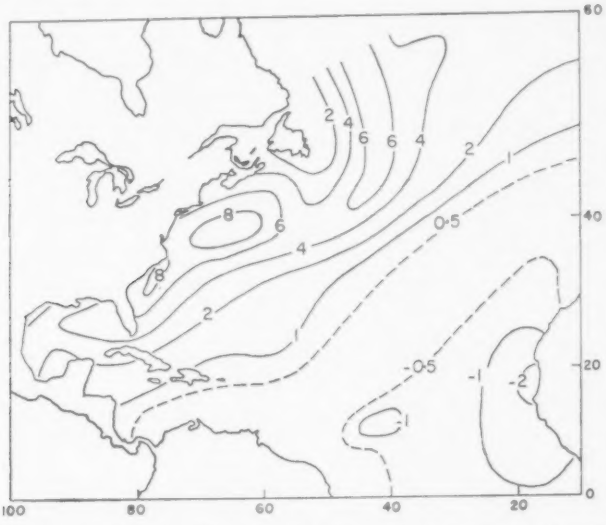

Fig. 5. Mean temperature difference (Fahrenheit) between sea-surface and air. December, January and February. From "Atlas of Climatic Charts of the Oceans." U.S. Weather Bureau No. 1247, 1938.

DISCUSSION

The 18° water in the Sargasso Sea is formed by a convergence which appears to be active at the end of nearly every winter. The convergence is caused by the extreme difference between water and air temperatures in winter (Fig. 5) producing the water type $T = 18°$, $S = 36{\cdot}5‰$ in excess quantity. This water then flows southward along the density surface for $\sigma t = 26{\cdot}4$, or thereabouts. It is difficult to suggest why the 18° isotherm is favoured ; one might have expected that in an extremely cold winter, water in the region south of the Gulf Stream might be cooled to 17°C but this has never been observed and one must judge on the basis of existing measurements that anomalously cold winters merely produce a larger volume of water of the same type.

The salinity value of 36·5‰ is easier to understand since the convergence must draw on the surface waters to the south for its supply of water. These waters according to BÖHNECKE's (1936) atlas are close to that value. The Gulf Stream can be safely eliminated as a source since its surface temperature is too high and its surface salinity too low at all times of year to reach $\sigma t = 26{\cdot}4$.

The volume of 18° water can be roughly estimated by considering it as a wedge. The base of the wedge which represents the northern boundary of 18° water is 250 m thick and 2000 km long (east to west). The wedge tapers to its apex about 1500 km south of the northern boundary. The volume of water in the wedge is thus 375,000 km³.

Probably all of this water is not renewed at the end of each winter but if it were, the amount of water turned over would be immense. If it is assumed that the renewal takes place in about 11·6 days (roughly a million seconds) the turnover would average 375 million m³/sec during that period. If only 20 per cent were renewed, which seems conservative, the turnover would be 75 million m³/sec, or roughly the equivalent of the Gulf Stream's transport (ISELIN, 1940). The average southward velocity necessary to effect this transport (in the latter case) is 15 cm/sec which is well within the scope of modern current measuring devices.

The importance of 18° water to the study of general circulation is that it provides a simple example of the way the thermocline structure of the oceans is affected by the atmosphere at the sea surface. At present the different shapes assumed by the thermocline are only dimly understood. The influence of the late winter weather conditions south of the Gulf can be felt as far south as the Caribbean Sea (Fig. 3). If the Geostrophic Equation is to be believed these conditions must have considerable influence on the volume transport of the upper layers of the Gulf Stream.

There is good evidence that the same sort of convergence occurs south-east of Japan, south of the Kuroshio where similar winter weather conditions prevail. Here, however, the water at the inflexion is characterized by a temperature of about 16·5° (and a salinity of 34·75‰ at a depth of 250 m*). In both oceans there is a strong thermocline beneath the isothermal layer formed by the winter convergence. If we assume that these permanent thermoclines represent the bottom, the waters above resemble a small scale thermal model of the world oceans.

A parallel can be drawn, for example, between the shallow waters of the Sargasso Sea and the North Atlantic as a whole, if we consider the 18° water in the former case to be analogous to the North Atlantic Deep Water in the latter. In both cases it is important to realize that the largest quantities of water converged come very close to being a single water type : in the upper 400 m of the Sargasso Sea the water type is $T = 18°$, $S = 36{\cdot}5‰$; in the Atlantic as a whole the water type is potential temperature $= 2°C$, $S = 34{\cdot}9‰$.

MONTGOMERY (1958) has presented diagrams of potential temperature versus salinity for the Atlantic Ocean (and the world ocean) in which the volume of water for each 0·5°C increment of potential temperature and each 0·1‰ of salinity has been estimated. By far the largest node in his Atlantic Diagram (op. cit. Fig. 3) is between 1·5°C and 4°C and 34·8‰ to 35·0‰ which represents North Atlantic Deep Water. This node comprises 40 per cent of the entire volume of the North and South Atlantic, exclusive of adjacent seas.

The principal weakness in the analogy between the two water types is that new 18° water is abundantly available for convergence at the end of each winter in the northern Sargasso Sea while no appreciable quantity of water resembling $T = 2°C$, $S = 34{\cdot}9‰$ can be found within 2000 m of the surface in the North Atlantic at the present time. The conclusion (WORTHINGTON, 1954) that North Atlantic Deep Water is no longer being produced in bulk is strengthened by this comparison. However, it is clearly necessary to make a more careful investigation of the formative areas of both water

* A particularly fine example was provided by the Japanese Research Ship *Kosyu's* section " A " in August 1936 ; Hydrographic Bulletin, Special Number, No. 8. Maritime Safety Agency, Tokyo, Japan, p. 83.

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types in late winter in order to assess the climatic conditions which must prevail if large quantities of water are to be converged.

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Contribution No. 1015 *from the Woods Hole Oceanographic Institution. This research was sponsored by the Office of Naval Research under contract Nonr*-2196.

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INSTRUMENTAL NOTES

Effect of pressure upon the "protected" oceanographic reversing thermometer

(*Received* 22 *September* 1958)

INTRODUCTION

ACTUAL degree of protection offered by the shell of the usual "protected" reversing thermometer has been computed. It appears that in the average modern instrument errors of roughly 0·002° C per 1,000 m sea depth change can be expected. However, certain protected instruments having an exceptionally small air volume below the cork have been found to be influenced by external pressure changes to as much as 0·008° per 1,000 m particularly at great sea depths.

The oceanographic reversing thermometer of the so-called "protected" type is enclosed in a heavy glass cylinder, and because of this, it is relatively insensitive to change in external pressure. Nevertheless, it is not safe for the oceanographer to completely ignore pressure effects whenever the protected thermometer is to be used with precision at great depths. Direct test of protected instruments for hydrostatic errors is not easy and apparently is seldom done, however, the approximate magnitude of these errors may be computed from instrument dimensions and from the elastic properties of the glass protective cylinder. Such computations indicate (1) that the pressure effect frequently lies just below the magnitude of usual significance, but (2) that under certain circumstances these pressure errors may exceed what is tolerable.

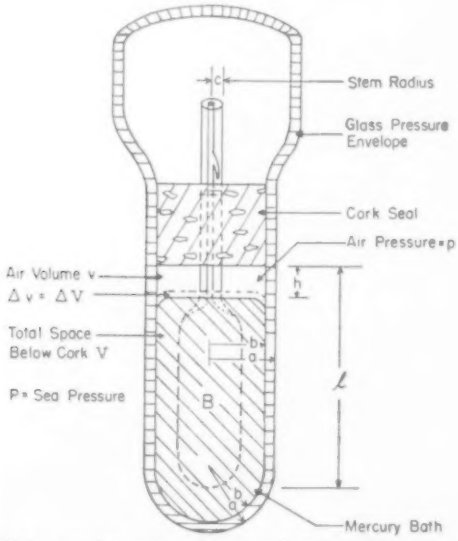

Fig. 1. The lower end of the usual "protected" reversing thermometer; the dimensions involved in a consideration of pressure error.

Fig. 1 presents the physical features involved. An increase of external pressure ΔP causes a decrease in interior dimensions of the sealed space below the cork and therefore a decrease in air volume Δv. Because of the compression of this air, a pressure at the outside surface of the thermometer bulb B is increased by Δp.

From the gas laws it can be shown that :

$$\Delta p = \frac{p_1 \Delta V}{v_1 - \Delta V} \tag{1}$$

where p_1 = initial gas pressure

and v_1 = initial gas volume (where the subscript is to mean an initial condition),
and ΔV = the change in total volume below the cork ; which is also the decrease in air volume, i.e. Δv.

Now this gas pressure change Δp squeezes a small amount of mercury from bulb B into the reading stem ; that is, it causes an apparent temperature increase $\Delta T'$. A numerical relationship can be obtained from the data relating to the " unprotected " thermometer where it is customary to express the pressure deviation.

$$\Delta T' = Q \Delta Z \tag{2}$$

where Q is an instrument constant and,
where Z is sea depth in metres. Converting thus to equivalent pressure units,

$$\Delta T' = 10\, Q \Delta p \tag{3}$$

where p is the pressure (atm) external to bulb, B.

Combining equations (1) and (3) gives for the pressure error :

$$\Delta T' = \frac{10\, Q p_1 \Delta V}{v_1 - \Delta V} \tag{4}$$

A reasonably approximate value of ΔV as a function of a change in external sea pressure ΔP can be deduced from the classical solutions for the compression of a thick-walled cylinder and for an end cap consisting of a thick-walled spherical shell since efforts usually are made by the glass blower toward maintaining these simple configurations. It can be shown (LAMB, 1916) that, approximately,

$$\Delta V = \frac{\pi}{E}\left[(5 - 4\sigma)\frac{a^2 b^2 l}{a^2 - b^2} + 3(1 - \sigma)\frac{a^3 b^3}{a^3 - b^3}\right] \Delta P \tag{5}$$

where the first term refers to a cylinder of length l, and the second term refers to the spherical end cap. The external and internal radii are a and b, respectively. E is Young's modulus, and σ is Poisson's ratio of the glass of the shell.

Numerical examples

For the physical properties of one common type of glass used in thermometers :

$$E = 6 \times 10^8 \text{ g/cm}^2 \text{ and,}$$
$$\sigma = 0{\cdot}25$$

For this glass, equation (5) reduces to :

$$\frac{\Delta V}{\Delta P} = 2{\cdot}1 \times 10^{-8}\left(\frac{a^2 b^2}{a^2 - b^2}\right) l + 1{\cdot}2 \times 10^{-8}\frac{a^3 b^3}{a^3 - b^3}, \tag{6}$$

where ΔP now is in g/cm^2 (i.e., cm of water roughly).

Case A : (for the dimensions of an average protected instrument)

Measurements were made upon several modern protected thermometers. In frequent instances, the following dimensions were representative :

$$a = 0{\cdot}75 \text{ cm}$$

$$b = 0{\cdot}60 \text{ cm}$$

$$c = 0{\cdot}20 \text{ cm}$$

$$l = 4{\cdot}5 \text{ cm}$$

$$h = 0{\cdot}6 \text{ cm}$$

from which the initial air volume is,

$$v_s = 0{\cdot}6 \text{ cm}^3$$

From these can be computed from equation (6)

$$\Delta V = 10^{-7}\,\Delta P = \text{cm}^3 \tag{7}$$

where ΔP is in g/cm^2.
Substituting for ΔV in equation (4) gives, for the common instrument,

$$\Delta T' = \frac{Qp_s\,\Delta P}{v_s - \Delta V} \times 10^{-6}, \tag{8}$$

which further reduces to,

$$\Delta T' = \frac{Qp_s\,\Delta Z \times 10^{-1}}{0{\cdot}6} \text{ approximately} \tag{9}$$

where ΔZ is changed to sea depth in 1,000 metre units.

Factors Q and p

The numerical value of p_1 depends upon the amount of compression given the air during the driving in of the cork, and upon the amount which has since diffused away. It is likely p_1 is nearly 1 atm in most older instruments, although in certain new ones it might temporarily amount to twice this, or even more. In passing it might be well to point out that equation (8) gives reason for the suspicion that in the protected reversing thermometer at least part of the well known zero point shift with age could be due to slow changes in p_1.

The factor Q can be measured by a non-destructive test involving breaking the mercury thread in an unusual manner. A few of such measurements have been made, and these have resulted in numerical values not greatly different from the values found for unprotected thermometers. It appears that Q should be not smaller than about 0·01°/m head of water.

Using these estimates for p_s and Q in equation (9), the rate of deviation due to depth can be estimated as

$$\frac{\Delta T'}{\Delta Z} = 0{\cdot}002° = \text{degrees/1,000 m depth change,} \tag{10}$$

with the major uncertainty resting in the values used for Q and p. Thus in the case of the usual modern instrument this error is a constant of the instrument which is practically independent of depth.

Conclusions regarding the averaged protected thermometer

Since it seems likely that p and Q each may in certain specimens reach values twice the value used in equation (9), there is no certainty that pressure errors as much as perhaps 0·01°/1,000 m depth change do not actually arise during ordinary oceanographic casts.

Case B : *Special circumstances (an overfilled thermometer used at great depths)*

Inspection of equation (4) will show that the pressure error is most likely to be significant whenever the pressure is large (i.e., ΔV is large), and also whenever the shell is overfilled with mercury (i.e., v_s is small).

One special protected thermometer which had actually been used at about 7 km depth was discovered to have an abnormally small air volume. Other parameters apparently were about the same as those listed in Case A above, however in this instrument,

$$v_1 = 0{\cdot}16 \text{ cm}^3.$$

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In this instance, and if the same nominal values for p and Q used above are assumed, the pressure deviation would have the rates :

0·006° C	between 0 and 1 km
0·007° C	between 4 and 5 km
0·008° C	between 6 and 7 km

In this case the increase in error with depth is due to the effect of V in the denominator in equation (4) ; it is physically possible for the denominator to approximate zero at very high external pressures.

A duplicate of this particular instrument was exposed to a hydrostatic test of 18,000 lb/in² while it was lying horizontal. The observation that part of the mercury in the bath was extruded through the cork seal under this exceptionally high squeeze induced thoughts as to the origin of this behaviour and thereby initiated the foregoing study.

From the above it would appear that a study of deep gradients with reversing type of thermometer should include a correction for the effect of pressure on the protected instruments and that special caution should be taken whenever comparing instruments differing in physical construction.

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A ship-borne nuclear-spin magnetometer

(*Received* 2 *December* 1958)

The department of Geodesy and Geophysics of Cambridge University began the development of a nuclear-spin magnetometer for use at sea in 1956 and since then extensive magnetic profiles of the total magnetic field have been obtained with its use.

The principles of operation of this type of instrument are described by Waters and Phillips (1956) and Cahill and Van Allen (1956) ; the development of this type of instrument for airborne use was made by Varian and Packard.

Briefly, the method consists in measuring the precessional frequency of the protons in a liquid (usually a hydrocarbon, or water) whose magnetic spin axes have previously been displaced from the direction of the earth's field by a superposed field. This frequency is independent of the angle of the spin axis relative to the direction of the Earth's field and is directly proportional to the value of the field. The advantage of this method is that the measurement of the field depends only upon the physical properties of the protons, and precise timing. Further, unlike the fluxgate magnetometer, no directional stabilization is required.

The superposed (or polarizing) field is applied to the liquid by a coil surrounding it. On account of the precession of the protons this coil has an alternating voltage induced in it during the period when the polarizing field is off and before the proton magnetic spin axes are realigned with the Earth's field. This alternating voltage has the frequency of the precession.

The voltage induced in the coil is given by the expression

$$V = kHH_e \sin^2 \theta \sin(\gamma H_e t)\, e^{-t/\tau}$$

where k is a constant depending upon the apparatus, the temperature and the physical properties of the liquid.

H is the polarizing field

H_e is the Earth's field

θ is the difference between the directions of the polarizing field and the Earth's field

γ is the gyromagnetic ratio of the protons in the liquid

t is the time after the polarizing field is switched off

τ is the thermal-relaxation time.

In water the value of V is such that $\frac{\gamma}{2\pi} = 4257{\cdot}8$. This results in the precessional frequency being approximately 2100 c/s in a field of 0·5 G.

The value of τ for water is approximately 3 sec so that the signal decays to e^{-1} times its initial value in approximately 3 sec. Similarly the relaxation time for the polarizing field is such that, for maximum signal, it must be maintained for at least 5 sec.

The maximum value of V is obtained when $\theta = \pi/2$ but the signal level may still be adequate at angles smaller than this. For example, by maintaining the polarizing field in a horizontal direction, the inclination of the earth's field provides, at all azimuths of the polarizing field, an adequate angle over a wide range of latitudes. In equatorial regions between, say, the latitudes 25 N to 25 S, where the inclination is small, it would be necessary to maintain the direction of the polarizing field more or less vertical if the signal level is to be adequate at all azimuths.

The details of our instrument are as follows :—

(1) The " Bottle " containing the water required for the measurement of the proton precessional frequency consists of a coil of ten layers of 23 swg copper wire, of external diameter 4 in., and of length 10 in. This coil is impregnated and closed at its ends with Araldite, and the container thus formed is watertight, non-magnetic, and is filled with distilled water.

(2) The coil is housed near the tail end of a " fish " which is made from fibre glass (plexiglass) tube, of length 5 ft, of $\frac{1}{4}$ in. wall thickness, and of 4 in. internal diameter. The fibre glass tube and the " bottle " are coaxial. This " fish " is provided with a hemispherical nose and cylindrical tail fins and is made negatively buoyant by an internal lead keel which stops the " fish " spinning about the axis of the tube. The end plugs of the tube are made from solid brass, and the watertight seals are provided by two " O " rings inset in the brass.

At the nose end of the " fish " there is a two stage tuned preamplifier and the two relays for switching the coil from the source of the polarizing current to the preamplifier input. These are kept as far from the " bottle " as possible in order to keep the magnetic field associated with them as small as possible in the vicinity of the " bottle." The distance is approximately 4 ft ; this is not quite adequate where measurements of field strengths are required to an accuracy of 1 γ. Because of this inadequate distance there is a heading correction to be applied which varies over a range of 6 γ. At speeds up to 10 knots, the " fish " swims at a depth of approximately 30 ft when towed 500 ft astern of the ship.

(3) The towing cable is 700 ft in length and enters the " fish " through a tube passing through the centre of the hemispherical nose. The cable is slightly greater than $\frac{1}{2}$ in. overall diameter and is sheathed with a P.V.C. skin approximately 0·1 in. in thickness. The electrical conductors consist of 7 P.V.C. covered flexible copper conductors laid around a P.V.C. covered flexible stranded steel stress core of breaking strain approximately 0·5 tons. The steady towing stress in the cable when the " fish " is 500 ft astern of the ship is approximately 70 lb wt at a speed of 9 knots. In order to avoid the effects of the ship's magnetic field it has been found necessary to tow the magnetometer a distance astern which is greater than two ship's lengths.

(4) The precessional signal from the " bottle " is connected to a two stage tuned amplifier in the ship. This amplifier is of approximately 100 c/s band width and with a centre frequency which can be varied in steps ; the output from this amplifier is squared in a Schmitt Trigger circuit. The sharp pulses from the Trigger circuit operate an eleven stage binary counter unit ; the last stage of this unit operates a " gating " circuit which at the first operation allows the signal from a 100 kc/s

crystal oscillator to pass to a six-decade counter unit reset to zero. When the last binary is operated for the second time the " gating " circuit closes and the decade counter units stop counting. The readings on these decade units are inversely proportional to the value of the Earth's field. The binary units are reset in such a way that 512 cycles of the precessional frequency are required before the final binary operates for the first time. This ensures that the electrical disturbance due to the switching process does not cause false readings on the decade units.

(5) The digital information from the six decades is recorded by a punch tape machine ; the machine also automatically punches at hourly intervals (or at any required time) the minute, the hour, the day of the month and the month. With observations at half minute intervals, the tape is changed once every eight hours. The tapes allow the reduction of the observations to be undertaken by an electronic computer.

(6) The digital output of the last three (units, tens and hundreds decades is converted into a voltage which is recorded on a visual potentiometer recorder. This recorder has a synchronous motor drive which is provided with a 50 c/s stabilised frequency supply derived from a 100 kc/s crystal unit. The motor also operates cams for the automatic cycling of the magnetometer. The sequence is as follows and is repeated every 30 or 60 sec :

(a) The binary and decade units are reset, and the potentiometer recorder pen drive is switched off

(b) The polarizing current through the " bottle " is switched on for 5 sec

(c) The precessional counting process follows (b) immediately and lasts approximately 1 sec

(d) The potentiometer recorder pen drive voltage is switched on

(e) The digital punch tape recorder operates.

(7) The polarizing current is approximately 1·0 A and is obtained from a rectified 50 V supply running from the ship's A.C. mains. It is not necessary that this supply should be electrically smoothed. The polarizing field is approximately 100 G.

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SHORTER COMMUNICATION

Amplification of transient response of the ocean to storms by the effect of bottom topography

(*Received* 13 *November* 1958)

VERONIS and STOMMEL (1956) showed that the ocean responds barotrophically to short-period large-scale fluctuations in the winds. Since motions in such a case extend all the way to the bottom it is natural to enquire whether irregularities in the topography of the bottom might modify the nature of the transient response; but VERONIS and STOMMEL did not consider this question.

The actual ocean bottom is very complicated in form. We do not propose to try to approximate this complexity in the following analysis. Also, it seems certain that irregularity of the bottom enhances the baroclinic mode's response (CHARNEY, 1957), but we consider here merely a barotropic model.

It is well known that in a homogeneous model the β-effect can be approximated by introducing a slope of the bottom upward in the y-direction. The equations which we will use are

$$\frac{\partial u}{\partial t} - fv = -g\frac{\partial \zeta}{\partial x} \tag{1}$$

$$\frac{\partial v}{\partial t} + fu = -g\frac{\partial \zeta}{\partial y} \tag{2}$$

$$\frac{\partial \zeta}{\partial t} + \frac{\partial}{\partial x}(hu) + \frac{\partial}{\partial y}(hv) = S(x, y, t) \tag{3}$$

where u and v are velocity components, ζ is the displacement of the free surface, f the Coriolis parameter, and $S(x, y, t)$ a driving agency – in this case explicitly a variable mass source : for example precipitation. There is no problem in making this mass source absorb the effects of other current producing mechanisms such as normal pressure, wind-stress, etc. (see STOMMEL, 1957). The quantity h is the variable depth of the ocean.

Assuming that the function S is of the form $S(x, y)\, e^{i\sigma t}$ we can eliminate u and v from the above equations and obtain

$$\left\{-\sigma g\left(h\nabla^2 + \frac{\partial h}{\partial y}\frac{\partial}{\partial y} + \frac{\partial h}{\partial x}\frac{\partial}{\partial x}\right) + igfJ(h, \;) + \sigma(f^2 - \sigma^2)\right\}\zeta = (f^2 - \sigma^2)\, S(x, y) \tag{4}$$

where the factor $e^{i\sigma t}$ has been removed from ζ.

The depth h may be written as

$$h = H(1 - \delta y + \epsilon\, b(x, y)) \tag{5}$$

This form is convenient because it separates the scale depth H from the small gentle slope δH (which we introduce to simulate the β-effect) and the bottom irregularity $H\epsilon\, b(x, y)$ where ϵ is a perturbation parameter which we define as the fraction of the total depth occupied by the submarine topography, and $b(x, y)$ is the functional form of the bottom topography with an amplitude of unity. This substitution makes equation (4) a linear partial differential equation in ζ with *non-constant* coefficients. If we regard ϵ as a small perturbation number ($\epsilon \ll 1$) and assert that the solution is of the form $\zeta = \zeta_0 + \epsilon\zeta_1 + \ldots$ we obtain the following equation

$$(L + \epsilon B)(\zeta_0 + \epsilon \zeta_1 + \ldots) = (f^2 - \sigma^2) S(x, y) \tag{6}$$

where L is the linear operator

$$L = \left\{ -\sigma gH \left[(1 - \delta y) \nabla^2 - \delta \frac{\partial}{\partial y} \right] + igfH \delta \frac{\partial}{\partial x} + \sigma (f^2 - \sigma^2) \right\} \tag{7}$$

and the non-constant coefficients are contained in the operator B

$$B = \left\{ -\sigma gH \left[b \nabla^2 + \frac{\partial b}{\partial y} \frac{\partial}{\partial y} + \frac{\partial b}{\partial x} \frac{\partial}{\partial x} \right] + igfH J(b, \ ) \right\} \tag{8}$$

To zero order, we therefore have the equation

$$L \zeta_0 = (f^2 - \sigma^2) S(x, y) \tag{9}$$

If $S(x, y)$ is taken to be of the form $S_0 e^{i(\mu x + \nu y}$ the solution of (9) is

$$\begin{aligned} \zeta_0 &= a_1 e^{i(\mu x + \nu y)} \\ a_0 &= \frac{S_0 (1 - s^2)}{f \{ s\lambda^2 \mu^2 + \nu^2 + i\delta\nu) - \lambda^2 \delta\mu + s(1 - s^2) \}} \\ \lambda^2 &= \frac{gH}{f^2} \qquad\qquad s = \frac{\sigma}{f}. \end{aligned} \tag{10}$$

This expression contains the effect of the large scale gentle slope $-\delta H$; and if $s \ll 1$ we are dealing with quasi-geostrophic motion of essentially the same kind as the planetary (Rossby, second kind) waves deduced by VERONIS and STOMMEL (1956, equation 4.3).

The first order perturbation effect of the bottom topography on ζ is given by the following equation equation with constant coefficients

$$L \zeta_1 = -B \zeta_0 \tag{11}$$

Consider a cellular form for the bottom topography : $b(x, y) = e^{i(mx + ny)}$. In this case the solution of equation (11) is

$$\zeta_1 = a_1 e^{i[(\mu + m)x + (\nu + n)y]}$$

$$a_1 = \frac{-s[\mu^2 + \nu^2 + n\nu + m\mu] - im\nu + in\mu}{s[(\mu + m)^2 + (\nu + n)^2 - i\delta(\nu + n)] - \delta(\mu + m) + \frac{s}{\lambda^2}(1 - s^2)} \times a_0 \tag{12}$$

Since we imagine that the scale of the bottom topography is smaller than the scale of the moving wind systems we must regard at least one of the quantities m and n as being larger than either μ or ν. The perturbation method works only for ranges of parameters where $\epsilon \zeta_1/\zeta_0 \ll 1$, or $\epsilon a_1/a_0 \ll 1$. On the other hand, the ratio A of the velocities produced by the bottom topographic perturbation to those produced on the flat-bottom model is of the form

$$A \equiv \frac{\epsilon a_1}{a_0} \left(\frac{m + n}{\mu + \nu} \right)$$

and can be considerably greater than unity without violating the conditions of the perturbation method. The quantity A may be called an amplification factor because it expresses the degree to which bottom topography can produce small scale geostrophic motions with greater amplitude than the planetary geostrophic motions of the scale of the wind-system.

By addition of elementary solutions (12) with various combinations of signs for μ, ν, m, n, σ, it is possible to construct solutions for all kinds of progressive and standing storm shapes and for submarine mountains with various configurations of crests. By Fourier superposition more elaborate forms can be obtained, but if the motive is comparison with transient current observed in nature, this model does not merit such elaboration. We are content merely to obtain an order of magnitude

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indication of whether the perturbation method works for the range of scales, etc., of interest, and roughly what the amplification of velocities is likely to be. Therefore we will restrict our attention to a definite range of scales and frequencies.

Consider a mid-latitude region where $f = 10^{-4}\,\mathrm{sec}^{-1}$ and the mean depth H is 4×10^5 cm. The slope δ corresponding to the equivalent β-effect is $10^{-9}\,\mathrm{cm}^{-1}$. Gravity is $10^3\,\mathrm{cm\,sec}^{-2}$ thus $\lambda^2 = 4 \times 10^{16}\,\mathrm{cm}^2$.

The dimensions of storms are in the neighbourhood of 3000 km wavelength both east-west and north-south. Therefore we take $\mu = \nu = 2 \times 10^{-8}\,\mathrm{cm}^{-1}$. We restrict the range of frequencies to 3 to 30 days ($2 \times 10^{-2} < s < 2 \times 10^{-1}$). Furthermore we consider mountains on the bottom with a range of wavelengths from 6 to 600 km ($10^{-5}\,\mathrm{cm}^{-1} \gg m$ or $n \gg 10^{17}\,\mathrm{cm}^{-1}$). Within this range the value of the ratio of amplitude of the vertical displacement is

$$\left|\frac{\epsilon a_1}{a_0}\right| = \frac{2i\mu}{sn}\,\epsilon$$

where we can interchange μ and ν or m and n. If the quantity should exceed, say, 0·2, the perturbation analysis would not be applicable, but this does not happen in the range under consideration. The amplification factor A for the velocities is

$$A \simeq \left|\frac{\epsilon a_1}{a_0}\right| \left(\frac{m+n}{\mu+\nu}\right) \simeq \frac{2i}{s}\,\epsilon$$

in the range under consideration. It is noteworthy that there is no strong effect of the wave-length of the mountains on the amplification factor. The only resonance frequency introduced by the bottom is at approximately $s = \delta/m$ from equation (12) and this is well outside the range of parameters under consideration. Low frequencies are favoured.

Dr. JOHN C. SWALLOW's measurements of transient currents off Portugal in May-June 1958 are compatible with this result. Take $\epsilon = 0{\cdot}20$, and the wavelength of the low topographic elements as 60 km (m and $n = 10^{-6}\,\mathrm{cm}^{-1}$). If the moving wind system occurs at bi-weekly intervals ($s = 0{\cdot}05$), the amplification factor is 8, hence the velocities of the small scale geostrophic motions associated with the bottom topography are of an order of magnitude greater than those with the scale of the moving wind-system; an estimate of the latter from Figure 2 of VERONIS and STOMMEL gives deep layer velocities of about 0·1 cm sec^{-1} so that we could expect geostrophic eddies of 60 km scale with velocities of around 1·6 cm sec^{-1}, and a frequency of once every two weeks. Shorter periods are not proportionately amplified. One concludes therefore that the irregularity of the bottom topography which actually occurs in the ocean is of dominant important in fixing the scale and amplitude of the transient barotrophic motions induced by storms.

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BOOK REVIEWS

Treatise on Marine Ecology and Paleoecology, Vol. 1, Ecology. Edited by J. C. HEDGPETH, Geological Society of America, Memoir 67, 1957, vi + 1296 pp. $12.50.

VOLUME 2 of this Treatise has already been reviewed. The main part of Volume 1 consists of a series of 29 essays by specialists on selected subjects presented between 1952 and 1956. These cover the most important physical and chemical factors influencing life in the sea and the different types of habitat. There are in addition detailed descriptions of certain areas (the Baltic, the Black Sea and the Sea of Azov, the Caspian and Aral Seas) which may seem to be given a disproportionate amount of space but which are nevertheless welcome because the literature on them is not readily available. Nearly half the book is concerned with the open sea and is therefore of particular interest to readers of this Journal.

The individual essays are generally excellent though they do not all follow a similar plan. Some deal with their subject in a general or descriptive way while others emphasize the bearing on ecology or paleoecology. A few of the chapters are rather slight e.g. that on fluctuations in littoral populations, and one or two are overweighted with detail e.g. that on mass mortality in the sea.

Each chapter has a useful reference list and at the end of the Volume there is a 200 page annotated bibliography compiled by 36 specialists whose aim is to provide a key to the recent literature of marine ecology.

The editor, Dr. Joel C. Hedgpeth, is to be congratulated not only for his success in bringing so much allied information together in this volume but also for the numerous chapters he himself has written either alone or as co-author. They are the most readable in the book.

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L. A. WALFORD: **Living Resources of the Sea.** *Opportunities for Research and Expansion.* Ronald Press Co., N.Y., 1958, XV + 321 pp., 23 maps, 17 tables.

IN the furtherance of its aims the Conservation Foundation of the United States has sponsored or published a number of books and some years ago it asked DR. LIONEL A. WALFORD, Chief of the Branch of Fish Biology, Fish and Wildlife Service this question. " What scientific researches, apart from those which are in progress would contribute significantly toward learning how to enlarge the yield of food from the sea in answer to human needs ? " The reply is the important and timely world policy document I now review.

The first part " The Marine Wilderness " is at pains to point to fields and methods which might make for a better marine yield and help to remedy world protein starvation. The bearing of conservation, taxonomy, environment, ecological principles, fish behaviour, brackish water culture, harvesting plankton, disease, poisons and design for fishing vessels and gear, are examined in turn. Rather surprisingly conservation is dealt with as a subject best left to Government experts although it has obvious importance to the ecologist who deals with animal numbers. The harvesting of plankton as food is another idea which one feels is not regarded as a very promising line in spite of its enormous potential. However, the rest are advocated with enthusiasm as the subjects of special study by laboratories and institutes to be set up particularly in backward countries and near areas from which we have insufficient knowledge.

The backbone of these institutions would be an environmental studies laboratory where the appropriate ecology could be studied and, associated with which, most of the other activities could be carried on. Together with these there would be a revival of the old style museums and their infusion

with financial support and zeal for a new taxonomical approach. On account of the inevitable limitations of space it has obviously not been easy to develop the new theories on environmental, ecological and " new look " taxonomic studies, and I am left with the feeling that much more effort will be necessary to produce the required substantial support for these views.

The last third of this work, Part II " Resources of the Sea," examines the groups of natural resources, invertebrate animals, fishes, reptiles, mammals and seaweed as present and potential assets.

The principal constituent of these is represented by the fishes, only a few of the 25,000 species of which are used. However, the better exploitation of the sorts we can use and the spread of modern methods to the coastal shelves of backward countries and similar measures might rather less than double the present yield. Outside this, there is the possibility of utilizing new stocks, such, for instance, as the oceanic tuna of the Atlantic and parts of the Indian and Pacific Oceans, the use of ground fishes on the deeper parts of the continental shelves and perhaps by inventing new methods such as electric light or electric currents to attract and pump on to a ship the enormous numbers of bathypelagic fish that are thought to constitute the Deep Sea Scattering Layer in all the Oceans.

Winding up Dr. Walford refuses to make an estimate of what is the likely increase to be obtained from the resources conjectured in the last paragraph but instead he makes a final plea for the expenditure of money on a comprehensive effort to fill the gaps in our knowledge by getting together scientists who will be prepared to look at the world scene without being limited by their local tradition.

The book is easy to read and in spite of the scope of the subject and the immense amount of scholarly reading that has obviously gone to its making, the information is put over with no sense of strain. A great deal of information is presented on well annotated maps of the world. This is an excellent idea, but I found the size of the maps used made some of the data a little cramped, and I believe that attention to this matter in any subsequent edition would be rewarding.

Comprehensive research on all the lines suggested and in all the potentially valuable areas may seem a council of perfection to some. Nevertheless, I am sure that it is the sound initial approach, an approach, however, that may be found capable of reduction and simplification as when, for instance, the elucidation of environmental structure in any area may produce laws that would explain the position elsewhere.

Fisheries Laboratory
Lowestoft, Suffolk

R. S. Wimpenny

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NEWS AND NOTES

Notice to all persons expecting to attend the International Oceanographic Congress at United Nations Headquarters, New York, 31 August - 12 September, 1959

1. REGISTRATION DAY will start on Sunday 30 August 1959 at 10 a.m. at the Hotel Commodore, Lexington Avenue and 42nd Street, New York. The Commodore will be the hotel headquarters of the American Association for the Advancement of Science. All those who wish to attend any sessions of the Congress must register there on arrival even if late.

2. There will be a REGISTRATION FEE of $10.00 which will entitle the registrant to :

(a) obtain a badge, which will serve as a pass on entering the United Nations building

(b) receive a copy of the volume containing summaries for all papers being presented at the afternoon seminars

(c) invitations to social events

(d) information on points of interest in New York City.

3. A block of rooms has been reserved at reduced rates at the HOTEL COMMODORE for anyone wishing to attend the Congress. Single rooms will cost $8, $9, and $10 per night, double rooms (with two beds) will cost $13, $14 and $15 per night. All room prices are subject to an additional 5 per cent New York City Room Tax. It will be more economical to share a room with a friend. The hotel reservations should be arranged directly with the hotel.

The HOTEL COMMODORE is the hotel where the American Association for the Advancement of Science has arranged for special rates. These are reasonable for New York City. It is hoped that most participants in the Congress will stay here. As the hotel headquarters for the Congress, it will afford greater opportunity for informal gatherings.

4. The American Association for the Advancement of Science cannot be responsible for making individual hotel reservations. Anyone wishing more modest quarters should arrange for these through his local travel agent. The Association cautions that reservations should be made *well in advance*, no matter where one plans to stay. If no reservation has been made before the Congress opens, the Association will assist in locating suitable quarters. It can, however, give no assurance that any will be available or that, if available, they will be as reasonable and comfortable.

5. Anyone planning to attend the Congress from abroad should *Book Passage at once.*

(a) At the time of the Congress, North American tourists will be returning from Europe in time for their children to enter school and even now it is difficult to obtain passage by boat or plane.

(b) It is not too early to apply for a *U.S. visa for your Passport.* You should start *immediately* to communicate with your nearest U.S. Consulate to inquire what formalities are required for a U.S. visa for your passport.

6. The programme (given below) lists the lecturers and chairmen for the morning lecture series, which are grouped around several broad topics. These lectures will be in sequence and are designed to interest all oceanographers. Originally, it was planned that the three afternoon seminars, held simultaneously, would be based on the general theme of the three lectures, held that same morning. However, as the conveners' plans for the seminars developed, it became clear that this was impractical. The mutual and overlapping interests of three seminars thus scheduled not only made the organization of the individual seminars difficult, but also would make it impossible for anyone to attend all seminars of particular interest to him. The new schedule makes it possible to attend nearly all seminars in

closely related fields. There may still have to be slight modifications, such as the addition of extra sessions for certain seminars and, possibly, a few general sessions for papers on topics which do not fit within the scope of the seminars.

Morning Lecture Series

31 *August* 1959 – *History of the Oceans* AAAS Committee representative : **Prof. Roger Revelle,** Scripps Institution of Oceanography, University of California.

Chairman : **Dr. G. E. R. Deacon,** National Institute of Oceanography, Great Britain.

1. Shape and structure of ocean basins. **Prof. W. Maurice Ewing,** Lamont Geological Observatory, Columbia University, New York.
2. Forces and processes at work in ocean basins. **Sir Edward C. Bullard,** Cambridge University, Great Britain.
3. Stratigraphy of the deep sea. **Dr. Edwin L. Hamilton,** U.S. Navy Electronics Laboratory, San Diego, California.

1 *September* 1959 – *History of the oceans* (continued).

Chairman : **Prof. Hakon Mosby,** Geofysisk Institut, Universitet i Bergen, Norway.

1. History of sea-water. **Prof. G. E. Hutchinson,** Yale University, New Haven, Connecticut.
2. Origin of life in the ocean. **Prof. A. I. Oparin,** A. N. Bach Institute of Biochemistry, Academy of Sciences, U.S.S.R.
3. The marine climate record. **Prof. Gustaf O. S. Arrhenius,** Scripps Institution of Oceanography, University of California.

2 *September* 1959 – *Populations of the Sea* AAAS Committee representatives : **Prof. George Myers,** Stanford University, California, and **Dr. Lionel A. Walford,** U.S. Fish and Wildlife Service.

Chairman : **Prof. Enrico Tortonese,** Muse, Museo Civico di Storia Naturale, Genoa, Italy.

1. Paleobiogeography. **Dr. Preston E. Cloud,** U.S. Geological Survey.
2. Biogeographical boundaries – the shapes of distribution. **Dr. R. S. Glover,** Oceanographic Laboratory, Edinburgh, Scotland.
3. Evolution in the deep sea. **Prof. G. S. Carter,** Cambridge University, Great Britain.

3 *September* 1959 – *Popoulations of the Sea* (continued)

Chairman : **Dr. N. K. Panikkar,** Central Marine Fisheries Research Station, India.

1. The role of ethology in oceanography. **Dr. H. O. Bull,** Dove Marine Laboratory, Great Britain.
2. Physiology of marine organisms in relation to their environment. **Prof. H. Friedrich,** Institut für Meeresforschung, Bremerhaven, Germany.
3. Cultivation of marine organisms as a means of understanding environmental influences on populations. **Prof. Trygve Braarud,** Oslo University, Norway.

4 *September* 1959 – *The Deep Sea* AAAS Committee representative : **Mr. Henry M. Stommel,** Woods Hole Oceanographic Institution.

Chairman : **Prof. Georg Wüst,** University of Kiel, Germany.

1. Geochemistry and physics of circulation. **Dr. Harmon Craig,** Scripps Institution of Oceanography.
2. Special quantitative characteristics of the ocean bathypelagic and bottom life. **Prof. L. A. Zenkevich,** Institute of Oceanology, Academy of Sciences, U.S.S.R.
3. Turbulent transports. **Dr. Willem V. R. Malkus,** Woods Hole Oceanographic Institution.

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7 *September* 1959 – *The Deep Sea* (continued) AAAS Committee representative : **Prof. Gustaf O. S. Arrhenius,** Scripps Institution of Oceanography, University of California.

Chairman : **Prof. Carl W. Correns,** Göttingen University, Germany.

1. Distribution of pelagic sediments (biological and inorganic components). **Prof. M. N. Bramlette,** Scripps Institution of Oceanography.
2. Nuclear processes in pelagic sedimentation. **Dr. E. Picciotto,** Belgium.
3. Abyssal benthic organisms ; nature, origin, distribution and influence on sedimentation. **Prof. A. Fr. Bruun,** University Zoological Museum, Copenhagen, Denmark.

8 *September* 1959 – *Boundaries of the Sea* AAAS Committee representative : **Mr. Gordon G. Lill,** Office of Naval Research, Washington, D.C.

Chairman : **Dr. J. N. Carruthers,** National Institute of Oceanography, Great Britain.

1. Coupling of sea and air. **Dr. P. Welander,** Meteorological Institute, Stockholm, Sweden.
2. Spectrum of sea level. **Prof. Walter H. Munk,** Scripps Institution of Oceanography, University of California.
3. Problems of epicontinental sedimentation. **Prof. Ph. H. Kuenen,** Geological Institute, Groningen, Holland.

9 *September* 1959 – *Boundaries of the Sea* (continued)

Chairman : **Dr. B. Kullenberg,** Oceanografisk Institut, Göteborg, Sweden.

1. An estuarine model of the sub-Arctic Pacific Ocean. **Dr. John P. Tully,** Pacific Biological Station, Nanaimo, B.C., Canada.
2. The length of pelagic larval life in marine bottom invertebrates as related to larval transports and ocean currents. **Prof. Gunnar Thorson,** University Zoological Museum, Copenhagen, Denmark.
3. Surface films and their importance in exchange processes.

10 *September* 1959 – *Cycles of Organic and Inorganic Substances in the Ocean* AAAS Committee representative: **Prof. Fritz F. Koczy,** University of Miami.

Chairman : **Dr. Y. Miyake,** Central Meteorological Observatory, Tokyo.

1. Physical chemistry of sea-water. **Prof. Lars Gunnar Sillen,** Royal Institute of Technology, Stockholm, Sweden.
2. Biologically active substances. **Dr. C. E. Lucas,** Marine Laboratory, Aberdeen, Scotland.
3. Primary production. **Dr. J. H. Steele,** Marine Laboratory, Aberdeen, Scotland.
4. Balance between living and dead matter in the oceans. **Prof. W. D. McElroy,** Johns Hopkins University.

11 *September* 1959 – *Cycles of Organic and Inorganic Substances in the Ocean* (continued)

Chairman : **Prof. Thomas G. Thompson,** University of Washington, Seattle, Washington.

1. Air-ocean. **Dr. Erik Eriksson,** Meteorological Institute, Stockholm, Sweden.
2. Sea-water and sediment. **Prof. S. W. Brujewicz,** Institute of Oceanology, Academy of Sciences, U.S.S.R.
3. Vertical and horizontal transport in the ocean. **Dr. L. H. N. Cooper,** Marine Biological Association, Plymouth, Great Britain.

Afternoon Seminars

31 *August* 1959

1. Shape and structure of the ocean basins and the forces involved. Conveners: **Dr. Maurice N. Hill,** Cambridge University, Great Britain and **Prof. Harry H. Hess,** Princeton University, New Jersey.
2. Physical chemistry of sea-water and surface films. Conveners: **Prof. Dayton. E. Carritt,** Chesapeake Bay Institute, Johns Hopkins University, Maryland, and **Dr. Gifford C. Ewing,** Scripps Institution of Oceanography, University of California.
3. Biogeography and environmental influences. Convener : **Dr. Joel W. Hedgpeth,** Pacific Marine Station, Dilton Beach, California.

1 *September* 1959

1. Shape and structure of the ocean basins and the forces involved (continued).
2. Physical chemistry of sea-water and surface films (continued).
3. Bathypelagic organisms. Conveners : **Dr. Anton Fr. Bruun and Mr. Torben Wolff,** University Zoological Museum, Copenhagen, Denmark.

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2 *September* 1959

1. History of sea-water and the origin of life. Convener : **Dr. William W. Rubey,** U.S. Geological Survey.
2. The influence of land masses on the distribution of organisms. Convener : **Prof. K. O. Emery,** University of Southern California.
3. The role of ethology in oceanography. Conveners : **Dr. H. O. Bull,** Dove Marine Laboratory Great Britain and **Dr. T. J. Walker,** Scripps Institution of Oceanography, University of California'

3 *September* 1959

1. History of sea-water and the origin of life (continued)
2. Epicontinental sediments and nearshore sedimentary processes. Convener : **Dr. Robert S. Dietz,** U.S. Navy Electronics Laboratory, San Diego, California.
3. Primary production. Convener : **Dr. John H. Ryther,** Woods Hole Oceanographic Institution.

4 *September* 1959

1. Stratigraphy of the deep sea and the marine climate record. Conveners : **Dr. Cesare Emiliani,** University of Miami, and **Mr. William R. Riedel,** Scripps Institution of Oceanography, University of California.
2. Turbulent transports. Convener : **Dr. Willem V. R. Malkus,** Woods Hole Oceanographic Institution.
3. Cultivation of marine organisms as a means of understanding environmental influences on populations. Convener : **Dr. Dixy Lee Ray,** University of Washington, Seattle, Washington.

Afternoon Seminars – 2

7 *September* 1959

1. Stratigraphy of the deep sea and the marine climate record (continued).
2. Deep sea circulation. **Dr. Charles S. Cox,** Scripps Institution of Oceanography, University of California.
3. Physiology of marine organisms in relation to their environment. Convener : **Dr. Otto Kinne,** University of Toronto, Canada.

8 *September* 1959

1. Physical and biological processes in sedimentation. Convener : **Dr. E. L. Hamilton,** U.S. Navy Electronics Laboratory, San Diego, California.
2. Nutrient relationships. Convener : **Dr. Bostwick H. Ketchum,** Woods Hole Oceanographic Institution
3. Evolution and adaptation in the sea. Convener : **Dr. A. A. Buzzati-Traverso,** Universita di Pavia, Italy.

9 *September* 1959

1. Physical and biological processes in sedimentation (continued).
2. Estuarine and nearshore circulation. Convener : **Prof. D. W. Pritchard,** Chesapeake Bay Institute, Johns Hopkins University, Maryland.
3. Paleobiogeography. Convener : **Dr. Preston E. Cloud,** U.S. Geological Survey.

10 *September* 1959

1. Nuclear Processes in marine sedimentation. **Dr. Johannes Geiss,** University of Miami, Florida.
2. Sea-air interchange. Conveners : **Dr. Erik Eriksson,** Meteorological Institute, Stockholm, Sweden and **Dr. Bernhard Haurwitz,** High Altitude Observatory, Boulder, Colorado.
3. Biologically active substances. Convener : **Dr. Luigi Provosoli,** Haskins Laboratories, New York.

11 *September* 1959

1. Sea-water sediment exchange. Marine minerals. Convener : **Dr. Edward D. Goldberg,** Scripps Institution of Oceanography, University of California.
2. Spectrum of sea level. Convener : **Prof. Walter H. Munk,** Scripps Institution of Oceanography, University of California.
3. Balance between living and dead matter in the oceans. Convener : **Dr. Eugene Corcoran,** University of Miami, Florida.

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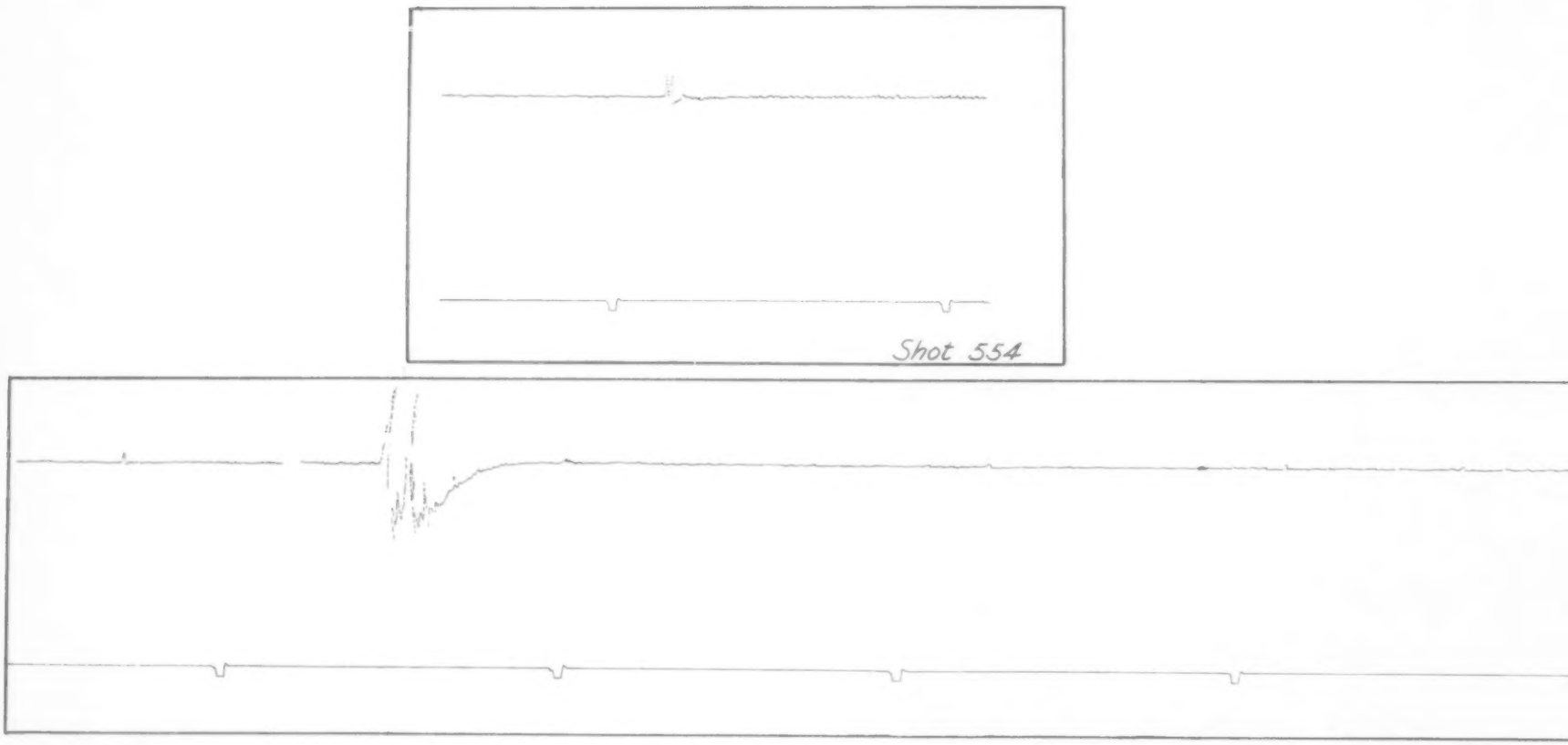
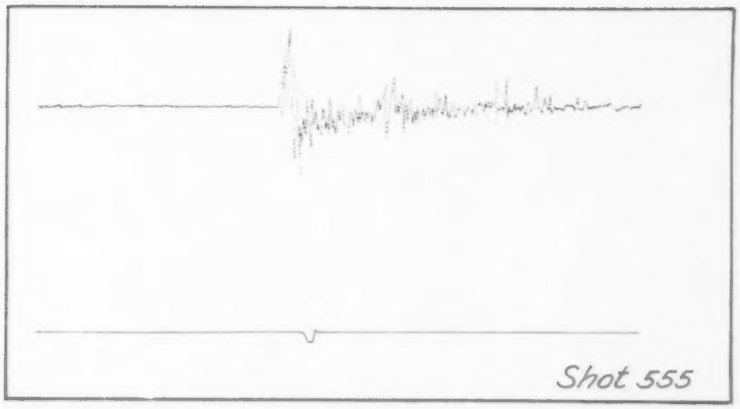
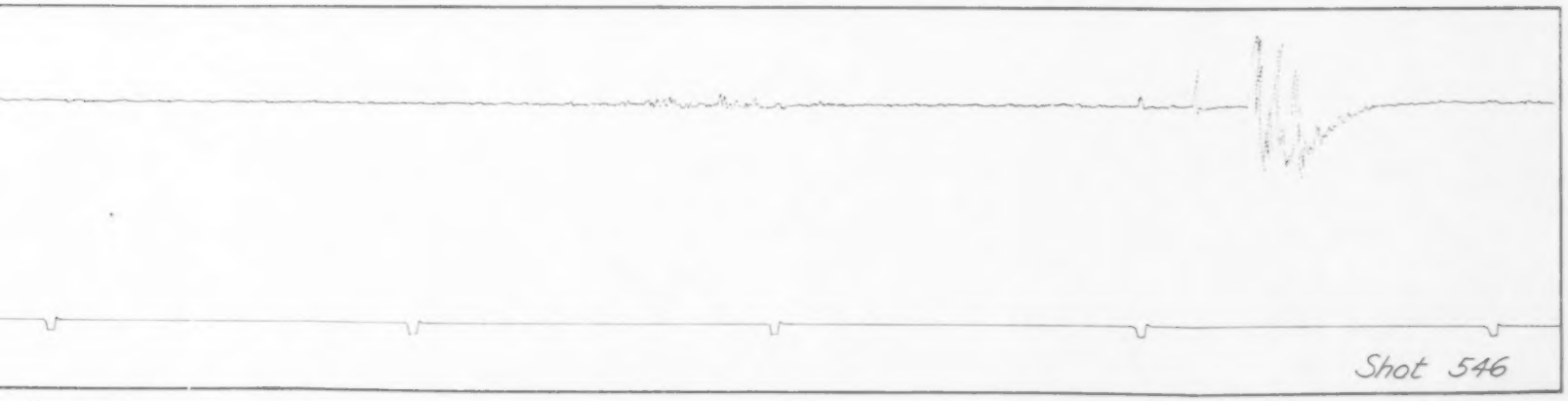


Fig. 8. Explosion soundi





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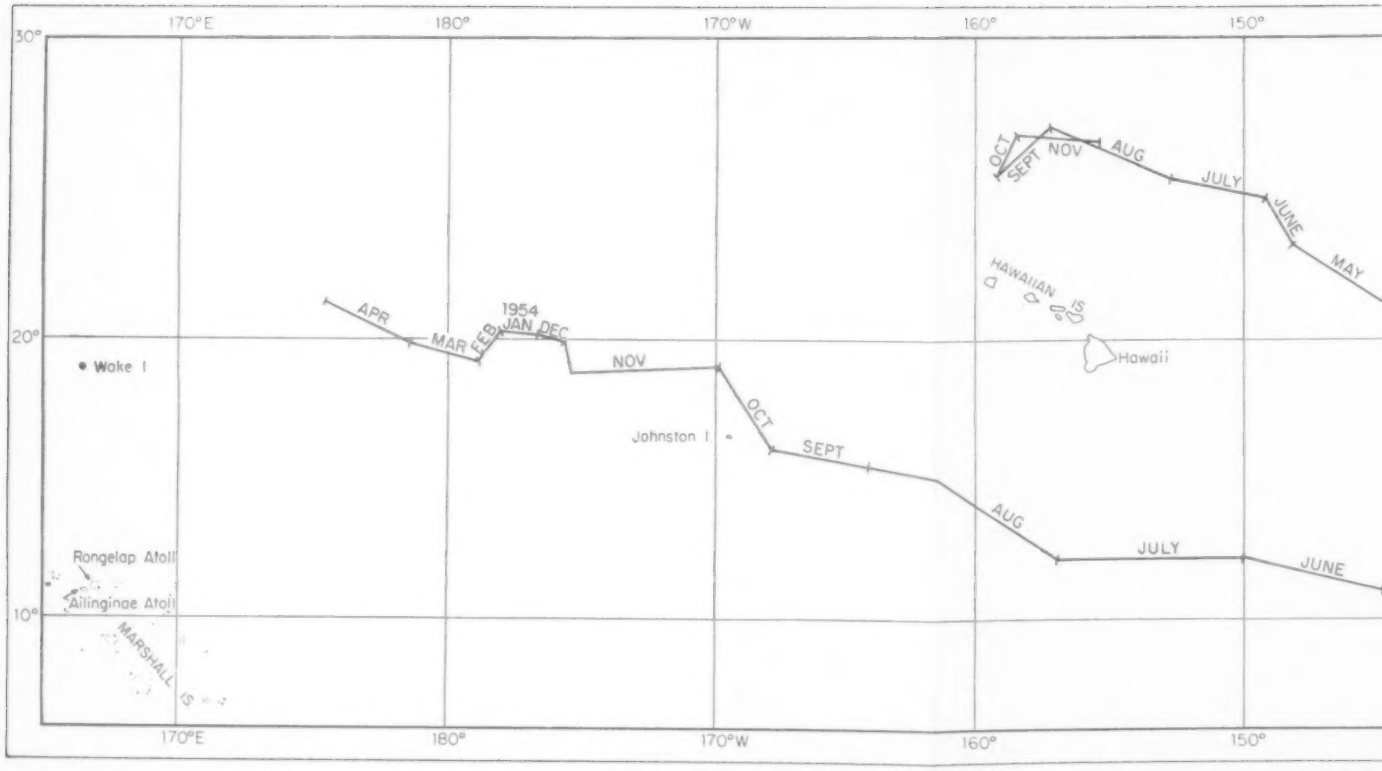
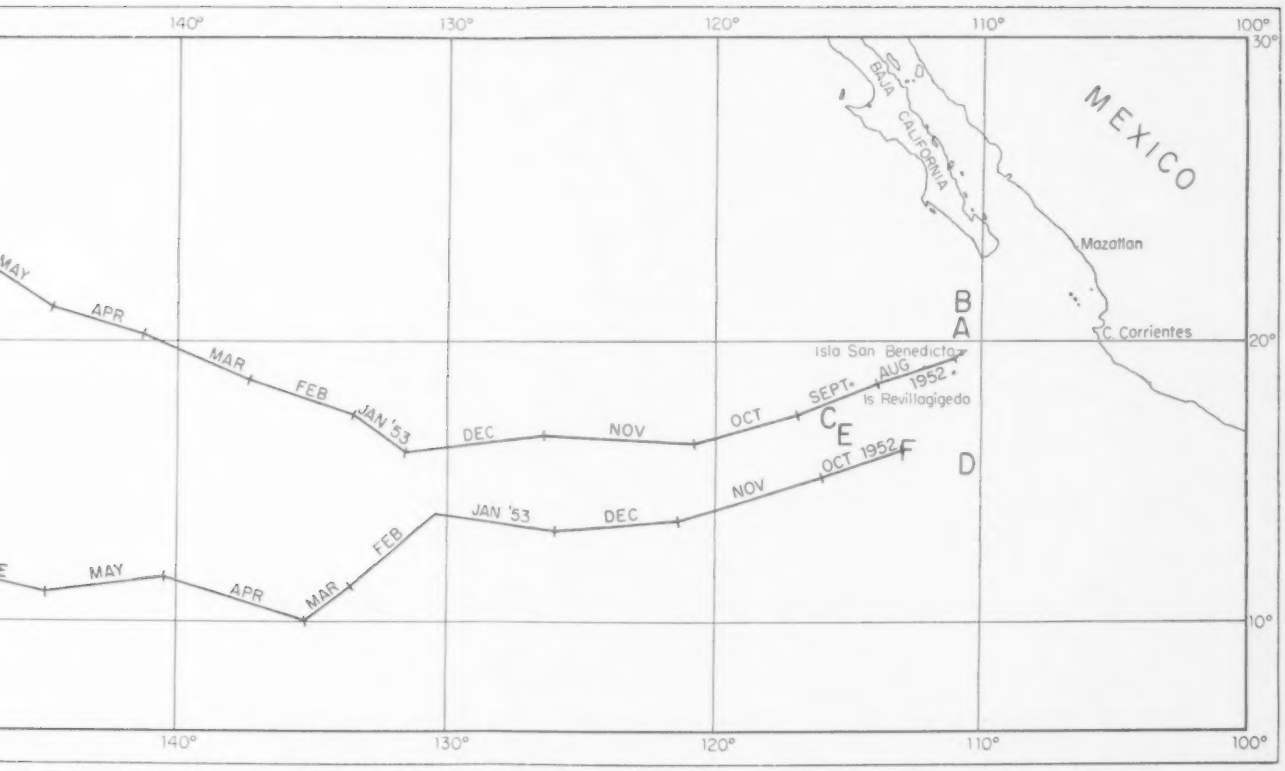
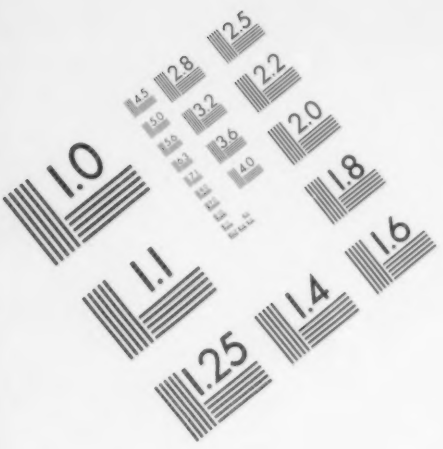


Fig. 1. Chart showing locations where Isla San Benedicto pumice was collec



collected and tracks of computed drift. See text for explanation.



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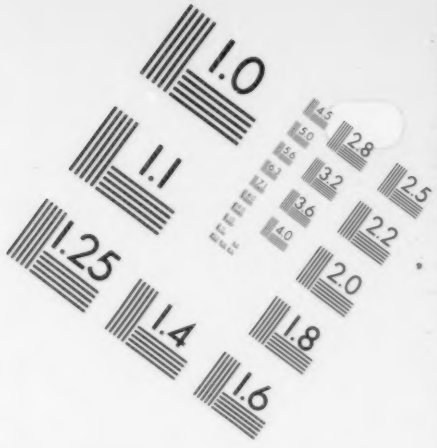

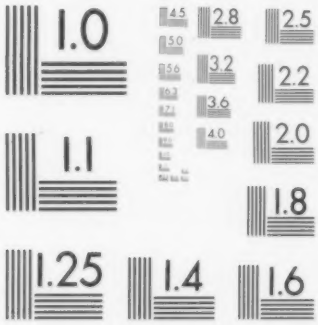

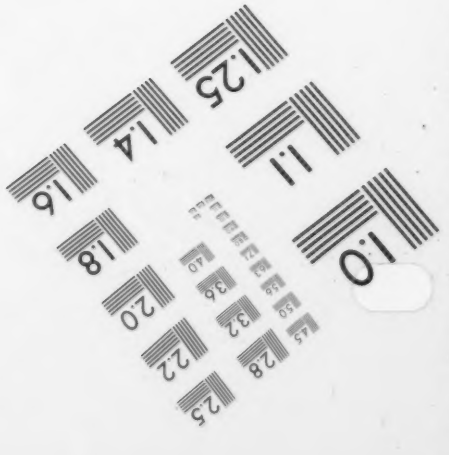

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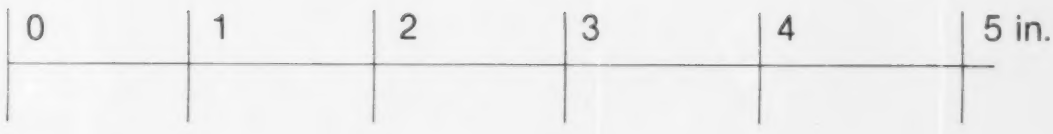

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